REMARKS

Interview

Applicants thank the Examiner for the interview held on May 25, 2006. During the interview the claims were discussed and possible amendment thereto.

Rejections Under 25 USC 102

The Office Action alleges that Pace anticipates.

The Office Action alleges that "Pace discloses that the sealing element is a brittle fracture (green ceramics, col. 7, line 13)."

Applicants respectfully disagree. The claims recite that the sealing element "consists of" glass, glass ceramic, or ceramic.

Pace on column 7, lines 1-14 teaches that

> A planar substrate 510 provided with conductive feedthroughs 520, 521 and terminals 522 for connection to the next level of electronic packaging is illustrated in FIG. 5a. Any suitable electronic insulating material may be used for the substrate 510. Suitable material include silicon, sapphire and ceramics and glass/ceramics comprising alumina, mullite, cordierite, beryllia, aluminum nitride, boron nitride, silicon nitride, silicon carbide and silicon carbide with a small percentage of beryllia.
>
> The feed-throughs 520 and 521 should have good conductivity and preferably maintain a hermetic seal. Refractive metal feed-throughs of tungsten or molybdenum prepared by the co-firing metal pastes in green ceramics provide hermetic feed-throughs. (Emphasis added.)

The last sentence does not mean and does not convey to one of ordinary skill in the art that the feed-throughs "consist of" brittle-fracture material. They are not made from only green ceramics or from firing a mixture of green ceramics and metal pastes.

The planar substrate 510 can be, e.g., ceramic or glass/ceramic, which can be produced by firing green ceramics or green glass/ceramics, and the metal feed-throughs, which are clearly taught to be made of the refractive metals of tungsten or molybdenum, can be produced by firing metal pastes. The term "co-firing metal pastes in green ceramics provide hermetic feed-throughs" means that the metal paste which will become the metal feed-through upon firing, is placed in green ceramics (not in admixture therewith), e.g., the paste is placed in a hole in the green ceramic. The latter green ceramic will become the

planar substrate upon firing, and the tungsten or molybdenum metal paste will become the metal feed-through. The two are co-fired to yield a product, which is a metal feed-through hermetically sealed within a hole in a ceramic or glass/ceramic planar substrate. Thus, overall, the feed-through does not consist of only brittle fracture material, but is rather a metal feed-through which provides the conductivity needed for the prior art application. Such a metal feed-through component is excluded from the instant claims. Therefore, there is no anticipation of any of the claims.

Although not necessary for purposes of the rejection, applicants separately address some of the dependent claims and also provide a submission which demonstrates the structural differences in the products prepared by methods claimed and by a method taught by Pace, i.e., chapters 3 and 4 from a book titled *Principles of Welding, Processes, Physics, Chemistry, and Metallurgy*, by Robert W. Messler, Jr., John Wiley & Sons, 1999. Pages 18-21 from this book have been submitted to the record previously.

The new material submitted from Messler teaches the various welding methods in the art, their advantages, and the differences in the obtained products achieved with the various welding methods.

In addition, applicants once again point to the pages already submitted from this reference to demonstrate the structural differences in the products obtained by welding methods as claimed versus methods where the sealing element is melted, i.e., fired, into the opening. On page 19, a figure having parts (a) to (e) demonstrates the effect on the structure of the materials bonded by a variety of welding techniques. Figures (a) and (b) demonstrate the effect on the structure of the bonded materials of a cold and hot pressure welding process; see accompanying discussion on page 18, about the middle of the page to page 20, about the middle of the page, discussing the attendant changes in properties of the structure of the materials when pressure welded. The effect on structure of a diffusion weld process is demonstrated in the Messler figure part (c). Figures (d) and (e) demonstrate the effect when material (the parent or a substrate) is melted; see accompanying discussion on page 21, first full paragraph, discussing the attendant changes in properties of the structure of the materials when material is melted. The structures of the products obtained by differing welding processes are different. As such Pace does not anticipate, nor does it render obvious the claimed invention.

With respect to various dependent claims, applicants provide the following comments.

With respect to claim 33, reciting the shape of the sealing material being a plate, spherical, conical or cylindrical shape, or claims 58 to 61 each reciting one of the previously mentioned shapes, Pace teaches that metal feed-throughs are fired to provide conductive feedthroughs through the substrate. Thus, the feed-throughs melt into the space provided for them and assume the shape of said space. As can be seen in the figure on the cover of the Pace patent, the space provided for the feedthroughs is a complex array of shapes through several layers of the substrate, wherein in each layer said space has a shape. In figure 5a to 5h, the same is illustrated, i.e., the steps of building a module according to Pace's disclosure is illustrated. See column 3, lines 66-67.

With respect to claim 34, reciting that the opening has the shape of a through-going cylindrical opening or through-going conical opening, or claims 58 to 61 reciting one of the previously mentioned shapes, Pace teaches the above mentioned shape for the space provided for the feedthroughs. Neither a through-going cylindrical opening or through-going conical opening is taught or suggested.

With respect to claims 58, 59 and 61, Pace only teaches embodiments where the shape of the sealing material assumes the shape of the opening as it melts into it to seal the same. The combination of a sealing material, shape different from that of the opening is not taught or suggested anywhere by Pace.

Nothing in Pace teaches with respect to claim 40 that the brittle-fracture material with at least one opening and the sealing material have substantially the same coefficients of thermal expansion, or with respect to claim 41 that the brittle-fracture material with at least one opening and the sealing material are made of the same material. Instead Pace teaches that the feed-throughs are made of a metal, such as tungsten or molybdenum (see column 7, lines 10-15, and that the substrate with the opening is a ceramic or glass/ceramic, etc. (see column 7, lines 5-10).

With respect to claim 47, nothing in Pace teaches or suggests an opening to a cavity, or with respect to claim 48 that such cavity is filled with a gas or liquid.

With respect to the product claims 53-56, nothing in Pace teaches, for example, a mirror, etc., comprising a molded element as claimed.

For all the foregoing reasons reconsideration is respectfully requested.

The Commissioner is hereby authorized to charge any fees associated with this response or credit any overpayment to Deposit Account No. 13-3402.

Respectfully submitted,

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PRINCIPLES OF WELDING

Processes, Physics, Chemistry, and Metallurgy

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PREFACE

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CHAPTER 4

NONFUSION WELDING PROCESSES

4.1. GENERAL DESCRIPTION OF NONFUSION PROCESSES

Nonfusion welding processes accomplish welding by bringing the atoms (or ions or molecules) of the materials to be joined to equilibrium spacing principally, but not exclusively, through plastic deformation due to the application of pressure at temperatures below the melting point of the base material(s) and without the addition of any filler that melts. Chemical bonds are then formed and a weld is produced as a direct result of the continuity obtained, always with the added assistance of solid-state diffusion. Often some heat is generated by or supplied to the process to allow plastic deformation to occur at lower stresses and to accelerate interdiffusion without causing or, at least, depending on melting (which, in the context of welding, constitutes fusion); hence the name nonfusion processes. The key feature of all nonfusion welding processes is that *welds can be produced without the need for melting or fusion.*

The three principal ways in which nonfusion welding is made to occur are (1) by pressure and gross deformation, in what is called *pressure welding*; (2) by friction and microscopic deformation, called *friction welding*; and (3) by diffusion, without or with some deformation, called *diffusion welding*. A fourth way is beginning to receive attention, namely processes that rely on solid-phase deposition, whether from an electrochemical reaction or vapor condensation, in what is called *solid-state deposition welding*. It is important to note that solid-phase diffusion (actually interdiffusion) between base materials or base materials and occasionally an intermediate is always involved in nonfusion welding, as it is to some degree in all welding processes, depending on temperature. Subclassification by the four methods just given simply refers to the predominant means of obtaining material continuity, with the fourth,

electro- or vapor deposition, just beginning to emerge as welding process embodiments.

While other sources of energy are possible (such as chemical reactions), mechanical energy is the most common and includes pressure sources and friction sources.[1] Both produce heat along with gross material transport as the result of the work done in causing deformation, but on a macroscopic scale for the pressure processes and on a microscopic scale for the friction processes. With chemical sources, bonds are formed in the solid state as the result of a chemical reaction. No deformation, either macroscopic or microscopic, is necessary. Examples are the aforementioned vapor deposition process and an electrochemical deposition process. While electrical sources could be used as a source for energy during nonfusion welding, most of the time the heat generated would (or could) cause melting, so the process would (or could) be occurring by fusion. An exception is when resistance is used to heat workpieces to the point at which they plastically soften, are squeezed together to obtain continuity, and diffusion weld together under the influence of the resistance heating (see Section 4.4.1.3).

There are eight major nonfusion welding processes: (1) cold welding, (2) hot pressure welding (using either pressure gas or forging); (3) roll (pressure) welding (hot, warm, or even cold); (4) explosion welding (which appears cold, but locally is occurring hot), (5) friction welding (using any of several types of motion), (6) ultrasonic welding (which is really friction welding with motion on a very small scale), (7) diffusion welding and diffusion brazing, and (8) deposition processes (using electrochemical reactions or vapor condensation). These are listed in Table 4.1.

Cold welding, hot pressure gas welding, forge welding, roll welding, and explosion welding all rely on substantial pressure to cause gross or macroscopic plastic deformation to produce a weld. Friction and, especially, ultrasonic welding rely on friction to cause heating and bring atoms or molecules together by microscopic plastic deformation to produce a weld. Diffusion welding relies on heating to accelerate diffusion to produce welds through mass transport in the solid state, with pressure sometimes playing a relatively minor role. Deposition processes rely on solid-phase diffusion once one material has been deposited onto another. No pressure is involved or required.

Nonfusion welding processes, as a group, offer several advantages over fusion processes. The general absence of melting and, typically, the low heat involved, minimally disrupt the microstructure of the materials being joined. As shown in Figure 2.2, there is no fusion zone and, usually, a minimal heat-affected zone in nonfusion welds. By precluding the need for melting, intermixing of the materials involved in the joint is minimal on a macroscopic

[1] Naturally, friction processes also involve pressure, since the force of friction arises from the product of the applied normal force and the coefficient of friction, $F = \mu N$. The coefficient of friction, μ, in turn, is determined by the state of the surface, which includes roughness and atomic cleanliness (i.e., freedom from oxide or tarnish or other contamination), as well as the presence of any lubricant.

TABLE 4.1 List of the Eight Major Nonfusion Welding Processes With Variations Within Each

1. Cold welding (CW)
    - Press welding
    - Forge welding
    - Roll welding
    - Toggle welding
    - Hydrostatic impulse welding
    - Shock-wave impulse welding
2. Hot pressure welding (HPW)
    - Pressure gas welding (PGW)
    - Forge welding (FOW)
3. Roll pressure welding (ROW)
    - Hot, warm, or cold roll welding
4. Explosion welding (EXW)
5. Friction welding (FRW)
    - Radial friction welding
    - Orbital friction welding
    - Rotational friction welding
        - Direct-drive welding
        - Inertia welding
    - Angular (reciprocating) friction welding
    - Linear (reciprocating) friction (or vibration) welding
    - Friction stir welding
    - Friction surfacing
6. Ultrasonic welding (USW)
    - Spot, ring, line, and seam USW
    - Microminiature welding
    - Microminiature thermosonic welding
7. Diffusion welding (DFW)
    - Conventional diffusion welding
    - Deformation diffusion welding
    - Resistance diffusion welding
    - Continuous seam diffusion welding (CSDW)
    - Diffusion brazing (DFB)
    - Combined forming/welding
        - Creep isostatic pressing (CRISP)
        - Superplastic forming/diffusion bonding (SPF/DB)
8. Solid-state deposition welding
    - Electrochemical deposition
    - Vapor deposition
    - Chemical vapor deposition
    - Chemical reaction bounding

Variations

TABLE 4.2 Relative Advantages and Shortcomings of Nonfusion Welding Processes

Advantages	Shortcomings
1. General absence of melting and, thus, solidification (so, structure is retained)	1. Stringent requirements for cleaning joint faying surfaces for some processes (e.g., CW, ROW, HPW, DFW, and solid-state deposition welding)
2. Low heat input (minimally disrupts microstructure)	2. Elaborate tooling is required for some processes (e.g., DFW)
3. Wide variety of process embodiments	3. Challenging inspection of joint quality
4. Applicable to many materials within a class as well as between classes (since there is little or no intermixing)	4. Repairing process-induced defects is difficult to impossible
5. High joint efficiency is possible for many situations where the same cannot be said for fusion welding processes	5. Processes require specialized equipment are rarely portable, and almost always must be automated

scale, so materials of dissimilar compositions can often be joined. Nonfusion processes are thus ideal for joining dissimilar materials, even from different basic classes or of totally different basic types, that would otherwise be chemically incompatible. A principal example is ceramic-to-metal joining, or, as some authors incorrectly call it, "welding." The joint resulting from nonfusion welding typically is of very high efficiency. In fact, only a nonfusion process could ever produce a "perfect" weld; indistinguishable from the base material(s) in structure and properties. Process disadvantages relate to the surface preparation and tooling required to produce acceptable joints and difficulties associated with inspecting and repairing defective joints. Relative advantages and shortcomings of nonfusion welding processes, as a group, are listed in Table 4.2.

Let's now look at the major subcategories and specific processes.

4.2. PRESSURE (NONFUSION) WELDING PROCESSES

As the name implies, nonfusion *pressure welding processes* primarily depend on the application of significant pressure to obtain metallic continuity and produce welds. Pressure processes can be performed cold or hot, so the first major subdivisions are *cold welding* and *hot pressure welding* processes. However, there are also processes that depend on rolling (from pressure rolls) or explosions (from explosives) for the pressure needed to obtain metallic continuity. The former can be performed hot or cold, while the latter are said

to occur cold, but really rely on heat that is highly localized at the joint interface arising from highly localized high-strain-rate plastic deformation and friction heating by violently expelled air.

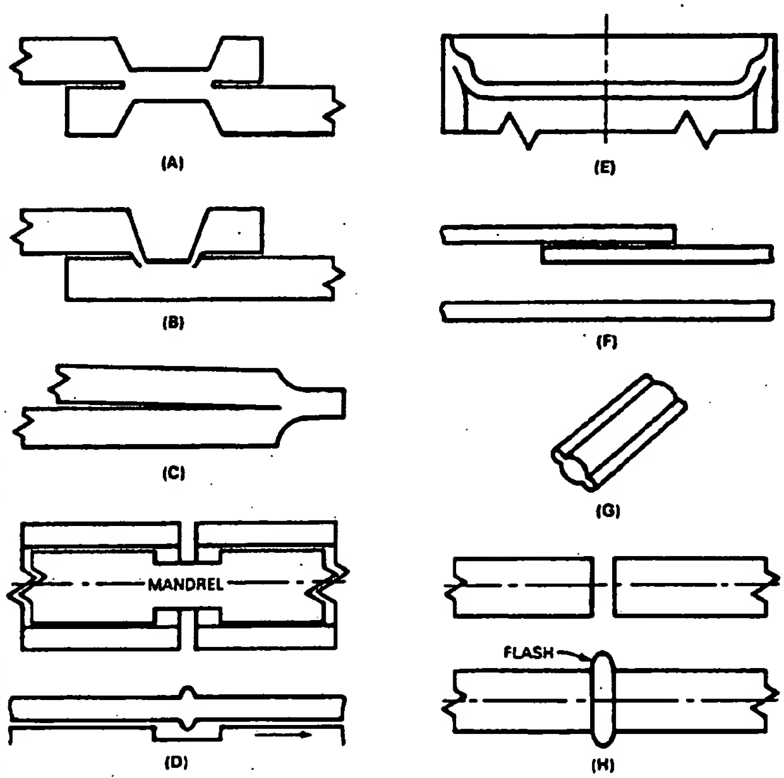
4.2.1. Cold Welding Processes

According to the American Welding Society (AWS), "Cold welding (CW) is a solid-state process in which pressure is used at room temperature to produce coalescence of metals with substantial plastic deformation at the weld." As a subgroup, cold welding processes are characterized by a notable absence of heat, whether applied from an external source or generated internal to the process itself. To achieve the required plastic deformation, at least one of the metals to be joined must be highly ductile and not exhibit extreme work hardening. Given this requirement, face-centered cubic (fcc) metals and alloys are best suited to cold welding. Prime examples of materials that are easily cold-welded are Al, Cu, and Pb, and, to a lesser degree, Ni and soft alloys of these metals such as brasses, bronzes, babbitt metals, and pewter. The precious metals, Au, Ag, Pd, and Pt, are also ideally suited to cold welding, as they are face-centered cubic (soft) and are almost free of oxides that can interfere with obtaining needed metallic continuity. (Recall, cold welding of precious metals is the oldest known welding process, as mentioned in Chapter 2.)

Cold welding is ideally suited to the joining of dissimilar metals since no intermixing of the base metals is required or obtained. This allows inherent chemical incompatibilities that would prevent or make fusion welding difficult to be overcome. The best example is the cold welding of relatively pure aluminum to relatively pure copper to produce electrical connections. Of course, there is the possibility that brittle intermetallics (e.g., Al_2Cu) will form later, either during postweld heat treatment or in service, say by resistance heating in the electrical connector.

Typical joint configurations for producing cold welds are shown in Figure 4.1. Note that every configuration is designed to allow or facilitate significant plastic deformation either in butts or laps. Typical lap weld indentor configurations used in cold welding are shown in Figure 4.2. The power for producing deformation may be applied by mechanical or hydraulic presses, rolls (as in roll welding, Section 4.2.3), or special tools (e.g., hand-operated toggle cutters). An impulse from a hydraulic or electrical source (e.g., capacitor discharge) can also be employed to force material together to effect a weld. Regardless of the method by which pressure is applied and metal is deformed, successful cold welding requires clean metal faces in contact to allow metallic continuity to be obtained. Cleaning can be accomplished mechanically using brushes or abrasives or chemically using acidic or alkaline etchants or pickling solutions, or using both methods.

Applications for cold welding are quite limited, largely by the requirement of stringent cleanliness, which is not easy to obtain in production environments. Nonetheless, when freedom from heat effects is critical, cold welding is obviously the best choice.

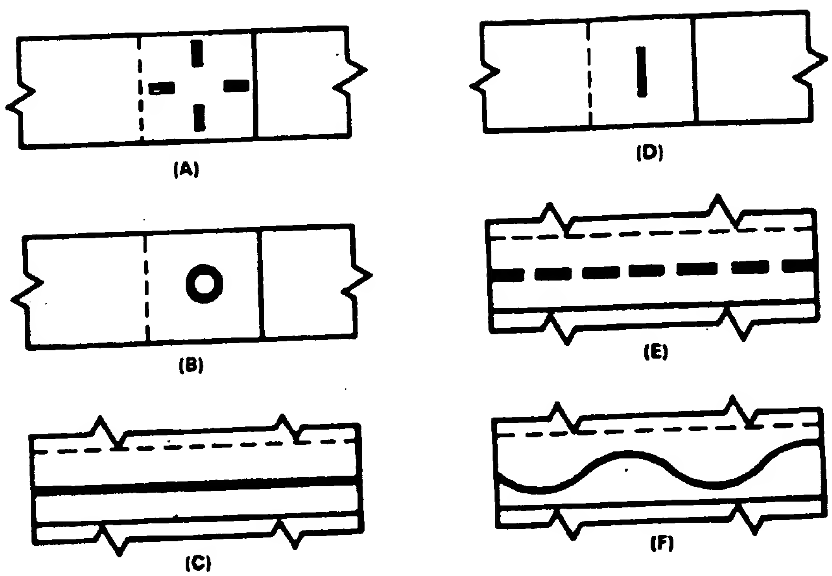


(A) LAP WELD, BOTH SIDES INDENTED; (B) LAP WELD, ONE SIDE INDENTED; (C) EDGE WELD, BOTH SIDES INDENTED; (D) BUTT JOINT IN TUBING, BEFORE AND AFTER WELDING; (E) DRAW WELD; (F) LAPPED WIRE, BEFORE AND AFTER WELDING; (G) MASH CAP JOINT; (H) BUTT JOINT IN SOLID STOCK, BEFORE AND AFTER WELDING.

Figure 4.1 Schematic of typical joints for producing cold welds. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

4.2.2. Hot Pressure Welding

According to the AWS, "Hot pressure welding (HPW) is a solid-state welding process that produces coalescence of metals with heat and application of pressure sufficient to produce macroscopic deformation of workpieces." Vacuum or other shielding may be used to prevent severe oxidation contamination, which would interfere with obtaining metallic continuity. The two major embodiments of hot pressure welding are (1) pressure gas welding and (2) forge welding.



(A) AND (B), BAR TYPE; (C) RING TYPE; (D), (E), AND (F), INTERMITTENT AND CONTINUOUS SEAM TYPES

Figure 4.2 Schematic of typical lap joint weld indentor configurations used in cold welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

4.2.2.1. Pressure Gas Welding. *Pressure gas welding* (*PGW*) employs oxy-fuel gas welding to heat faying surfaces at the same time pressure is applied to force the parts together to produce a solid-state weld. Two subforms are the (a) *closed joint* and (b) *open joint* methods. In the closed joint method, the faces of parts to be joined are tightly abutted, then heated under the simultaneous application of moderate pressure to cause a predetermined degree of upsetting and welding. In the open joint method, the faces of parts to be joined are heated while separated, and then are brought together under pressure to cause upsetting and welding. To achieve the level and consistency of heating needed at the joint, along with the pressure needed to force the parts together, the pressure gas welding process is always automated or, more properly, mechanized.

Typical joint designs for pressure gas welding are shown in Figure 4.3. Metals welded by this process include low- and high-carbon steels, low-alloy steels, stainless steels, and nickel–copper Monels. Upset pressures typically range from 3 to 10 ksi (20 to 70 MPa).

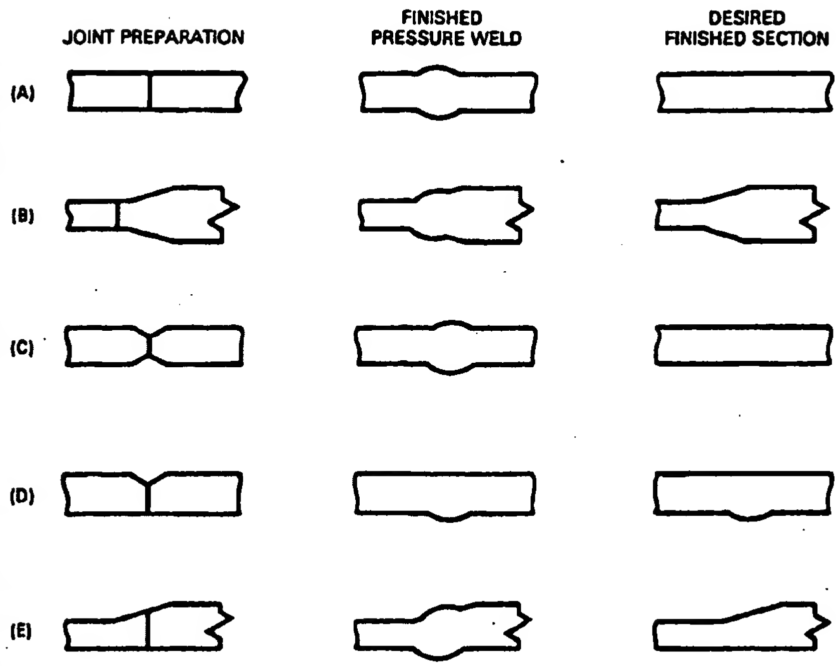


Figure 4.3 Schematic of typical joint designs for pressure gas welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

4.2.2.2. Forge Welding. According to the AWS, "*Forge welding* (FOW) is a solid-state welding process that produces a weld by heating workpieces to welding [hot working] temperatures and applying blows sufficient to cause deformation at the faying surfaces." Without question, forge welding was the earliest form of welding, and is still used today by blacksmiths, among others. The well-known and highly regarded Damascus steel swords made by ancient Syrians are an excellent example of ancient forge welding, while hand-forged chains and wrought-iron products are good examples of modern forge welding by blacksmiths.

Parts to be forge welded can be heated in an actual forge or forging press, or in a furnace or by other means until malleable. These heated parts are removed from the heating source, placed in contact (usually by overlapping), and forced together by either repeated blows or by continuous pressure. The former process variant is called *hammer welding*; the latter is called *die welding*, because it usually takes place in a die to maintain the part/joint shape. Typical joint designs for manual and automated forge welding are shown schematically in Figure 4.4a and b, respectively.

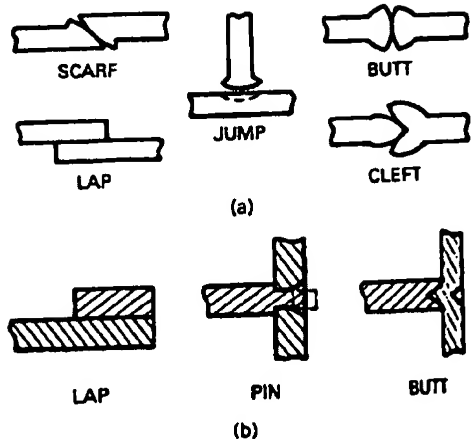


Figure 4.4 Schematic of typical joint designs for (a) manual and (b) automated forge welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

Among metals that can be forge welded are low-carbon steels (which is by far the most commonly forge-welded metal), high-carbon steel, and aluminum alloys in extruded forms. (The latter is being looked at as one means of joining aluminum alloy extrusions to produce space frames for aluminum-intensive automobiles. Hydraulically or electrically-induced impulses and/or shockwaves are used to produce these welds.) To facilitate bonding during forge welding, fluxes are often used, the most common being borax and fine silica sand, singly or in combination.

4.2.3. Roll Welding

In *roll welding* (ROW), one workpiece, usually in plate or sheet form, is caused to form primary chemical bonds and welds with another by having large numbers of atoms brought into continuity by deforming the two pieces using pressure from squeezing rolls or rollers. While the process can be performed cold or hot, it is almost always performed hot to reduce the power required and to preclude work hardening by relying on dynamic recrystallization. In fact, it is recrystallization that causes nucleation of new grains at the original interface and growth across that interface to produce a high-quality weld (see Section 2.2).

A well-known example of roll welding is the production of clad metals such as those used in the manufacture of copper-bottomed steel or stainless steel pots and pans (e.g., Revereware). It turns out, there are a number of applications that require clad metals for obtaining required properties, one popular one being to clad pure copper onto structural steel to enable the fabrication of tanks used in electrochemical processing (e.g., plating or dissociation).

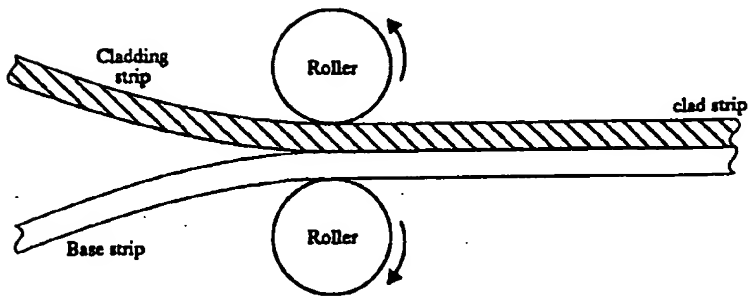


Figure 4.5 Schematic of a typical roll welding process producing clad metals.

Figure 4.5 schematically shows a typical roll welding process being used to produce clad metals.

4.2.4. Explosion Welding

Explosion welding (*EXW*) is a pressure-welding process that represents a special case. In explosion welding, the workpieces usually start out cold but heat significantly and extremely rapidly very locally at their faying surfaces during the production of the actual weld. As shown in Figure 4.6, the controlled detonation of a properly placed and shaped explosive charge causes the properly aligned workpieces (Figure 4.6a) to come together extremely rapidly at a low contact angle (Figure 4.6b). When this occurs, air between the workpieces is squeezed out at supersonic velocities. The resulting jet cleans the surfaces of oxides and causes very localized but rapid heating to high temperatures. Additional heating occurs as the result of high-strain-rate deformation in the immediate vicinity of the impacting pieces. The result of clean atoms coming together in large numbers is a metallurgical bond or weld. The weld bondline of explosion welds is typically very distorted locally, as shown in Figure 4.6b, reflecting severe but highly localized plastic deformation.

While not widely practiced because of the obvious requirement for intimate and highly specialized knowledge of explosives and their effects, explosion welding can provide some unique capabilities. Very heavy-section parts can be welded together, and over large surface areas, if required. Producing such welds would be virtually impossible by other means. Explosion welding is employed in the production of heavy-clad thick plates for use where heat, oxidation, corrosion, or wear resistance is needed, examples being AISI 304 clad to mild steel, and commercially pure (CP) titanium clad to mild steel. It is often performed under water to enhance the shock wave to move and deform material.

Explosion welding also has special value for producing transition joints for subsequent use in fusion welding two incompatible metals or alloys that cannot be directly welded. In such situations, explosion-welded combinations of two metals that are compatible with each substrate (i.e., one layer in the clad pair

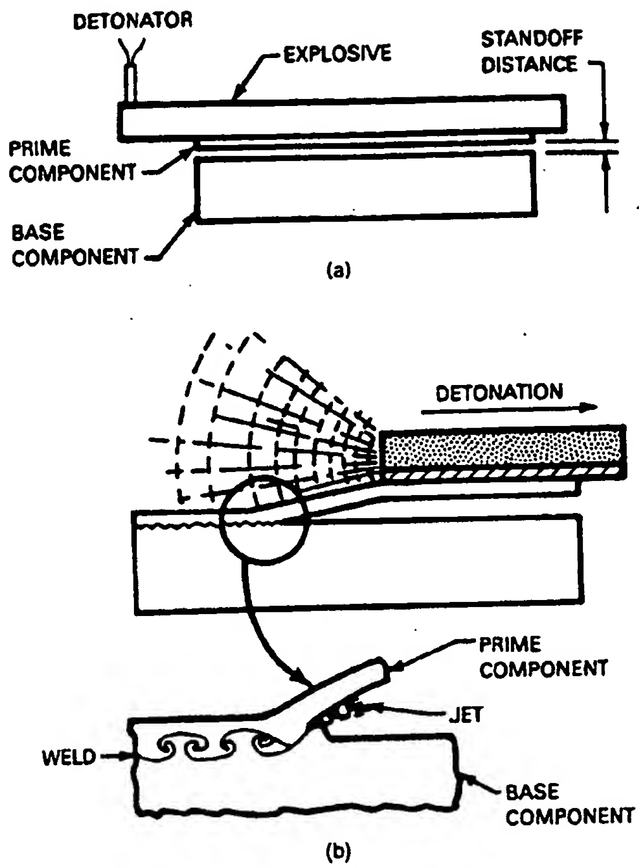


Figure 4.6 Schematic of explosion welding showing (a) typical component arrangement and (b) the action between components during welding. Note the turbulence that occurs at the interface to cause intermixing. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

to one substrate, the other layer to the other substrate) make up the transition piece, and the transition piece is then welded by conventional means (usually using a fusion process) to each substrate. The transition piece acts as a bridging member. Examples are Cu-steel, Cu-stainless steel, Cu-Al, and Al-steel. The latter are occasionally used to allow automobile body parts made from aluminum alloy to be resistance spot welded to parts made from steel.

Figure 4.7 shows that a large number of commercially significant pure metals and alloys can be joined by explosion welding.

	ZIRCONIUM	MAGNESIUM	COBALT ALLOYS	PLATINUM	GOLD	SILVER	COLUMBIUM	TANTALUM	TITANIUM	NICKEL ALLOYS	COPPER ALLOYS	ALUMINUM ALLOYS	STAINLESS STEELS	ALLOY STEELS	CARBON STEELS
CARBON STEELS	●	●			●	●	●	●	●	●	●	●	●	●	●
ALLOY STEELS	●	●	●					●	●	●	●	●	●	●	
STAINLESS STEELS			●		●	●	●	●	●	●	●	●	●		
ALUMINUM ALLOYS		●				●	●	●	●	●	●	●			
COPPER ALLOYS					●	●	●	●	●	●	●				
NICKEL ALLOYS		●		●	●			●	●	●					
TITANIUM	●	●				●	●	●	●						
TANTALUM					●		●	●							
COLUMBIUM				●			●								
SILVER						●									
GOLD															
PLATINUM				●											
COBALT ALLOYS															
MAGNESIUM		●													
ZIRCONIUM	●														

Figure 4.7 Commercially significant metals and alloys that can be joined by explosion welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

4.3. FRICTION WELDING PROCESSES

As a group, *friction welding* (*FRW*) *processes* employ machines that are designed to convert mechanical energy into heat at the joint to be welded using the relative movement between pieces. Coalescence of materials occurs under the compressive force of contact between workpieces moving relative to one another in rotation, or by angular or linear reciprocation.

Figure 4.8 schematically shows the basic steps involved in the friction welding process. The parts to be joined are moved relative to one another while under moderate pressure, frictional heating occurs and softens the material in the vicinity of the joint, and, then, an upsetting or forging pressure is applied to complete the weld. This final, forging step is what really establishes metallurgical continuity and bonding. The earlier steps cause heating and, simultaneously, scrub away any intervening oxide or tarnish.

There are three ways in which friction can be generated by the relative motion between workpieces, and these depend on the directions of that motion. The three motions are (1) rotation, (2) angular reciprocation, and (3) linear

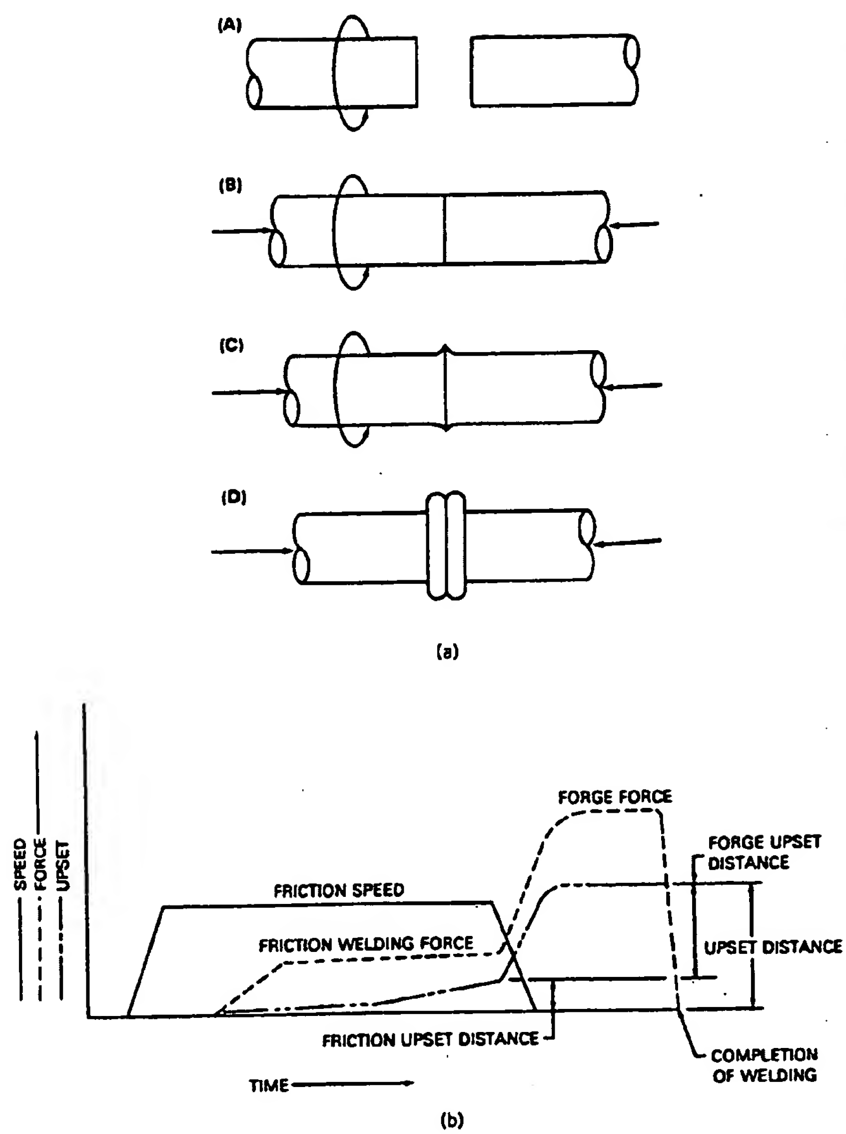


Figure 4.8 Schematic of the basic steps (a) and direct drive parameter characteristics (b) involved in friction welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

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reciprocation. If the amplitude of relative motion is very small and the frequency very high, in the range of ultrasound (greater than around 30 kHz), the process is called *ultrasonic* (*friction*) *welding*. There is, in fact, a relatively new variant of friction welding in which the parts to be welded are held still and frictional heating is generated by a rapidly rotating tool placed between the pieces under pressure. This variation is called (*friction*) *stir welding*. Each of these variations is described very briefly.

4.3.1. Radial and Orbital Welding

When rotation is used to accomplish friction welding, the force applied to bring the parts into initial contact and then to forge them together can be either parallel to the axis of rotation (axial) or perpendicular to the axis of rotation (radial). When a radial force is to be used, either the parts can be rotated relative to one another in what is known as *orbital friction welding* or the parts can be held stationary while a concentric collar or sleeve is caused to rotate in what is known as *radial friction welding*. Figure 4.9 schematically shows radial versus orbital friction welding.

Regardless of the particular variation, whenever rotational motion is employed to produce friction to produce a weld, there are restrictions on the shape of parts that can be joined. Clearly, only parts with rotational symmetry can be welded using rotational motion.

4.3.2. Direct-Drive Versus Inertia-Drive (Friction) Welding

When an axial pressure/forging force is used with *rotational friction welding*, two predominant techniques are employed. In the first, more conventional technique, the moving part is held in a motor-driven collet and rotated at a constant speed against a fixed part while the axial force is applied to both parts. Rotation is continued until the entire joint is suitably heated, and, then, simultaneously, the rotation is stopped and an upsetting force is applied to produce a weld. Key process variables are rotational speed, axial force, welding time, and upset force or displacement. This variant is called *direct-drive welding*. In the second technique, called *inertia-drive* or simply *inertia welding*, energy is stored in a flywheel that has been accelerated to the required speed by a drive motor. The flywheel is connected to the motor through a clutch and to one of the workpieces by a collet. The weld is made by applying the axial force through the rotating part to a stationary part while the flywheel decelerates, transforming its kinetic energy into heat at the joint faying surfaces. When done properly, the weld is completed when the flywheel stops. Key process variables are the flywheel moment of inertia, the flywheel rotational speed, the axial force, and the upset force. The actual process for both techniques is usually automated. Sometimes rotational friction welding processes are called spin welding.

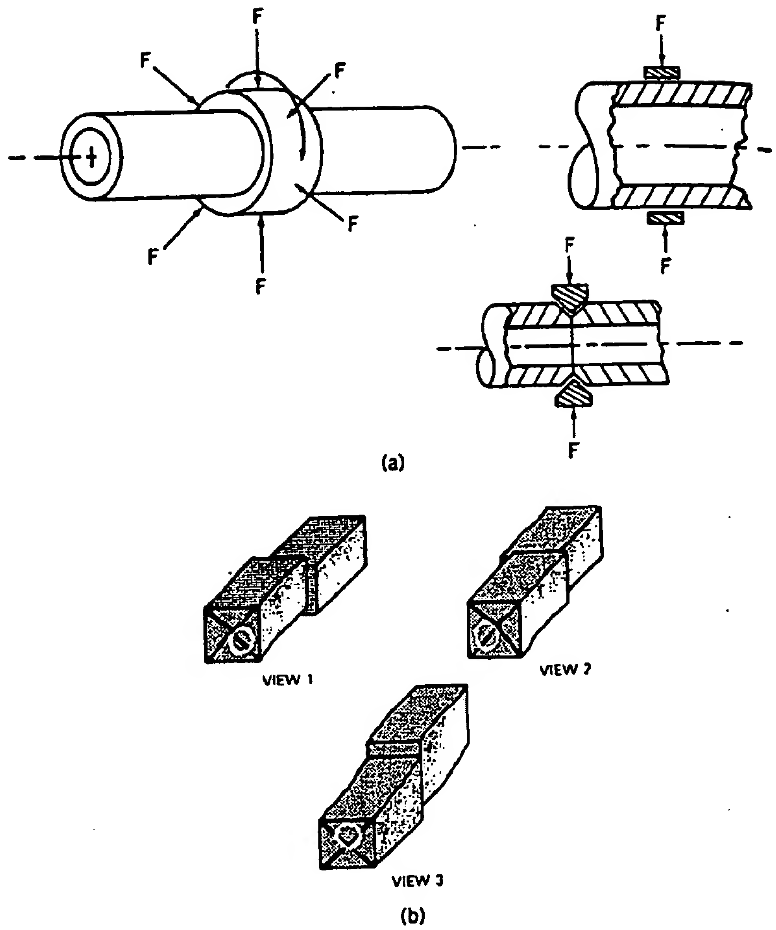


Figure 4.9 Schematic of (a) radial versus (b) orbital friction welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

Typical arrangements of rotational friction welding, whether using direct or inertia drive, are shown schematically in Figure 4.10.

4.3.3. Angular and Linear Reciprocating (Friction) Welding

It is also possible to accomplish friction welding using reciprocating motion between workpieces in contact throughout the process. This reciprocating motion can be angular, in which case the process is called *angular* (*reciprocat-*

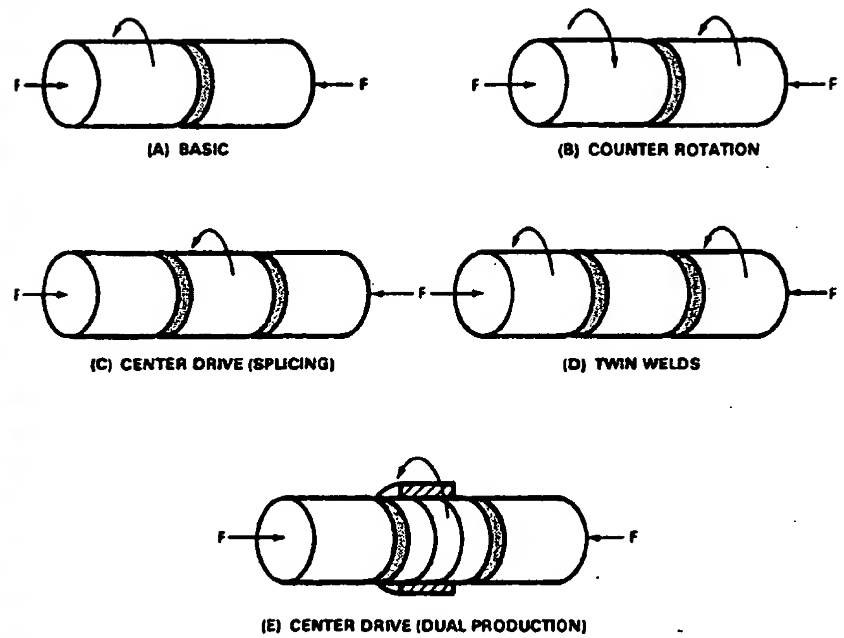


Figure 4.10 Schematic of typical arrangements of rotational friction welding. Note that the drive could be either direct or inertial for (A). (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.).

ing) *friction welding*, or linear, in which case the process is called *linear* (*reciprocating* or *vibration*) *friction welding*. Figure 4.11 schematically shows these two variations.

The fact that angular or linear reciprocating motion is being used to produce friction to produce a weld does not mean that there are not either restrictions on the shapes of parts that can be welded thereby, or that such welding will be trivial. The upset or forging force must be applied when reciprocation is halted and parts are properly aligned.

Figure 4.12 shows combinations of metallic materials that can be joined by friction welding. A variety of ceramic materials, as well as metal–ceramic combinations, can also be joined by this group of processes.

4.3.4. Ultrasonic (Friction) Welding

The source of motion in friction welding can be pure mechanical vibration or ultrasonically induced vibration. When ultrasonic vibration is employed, the

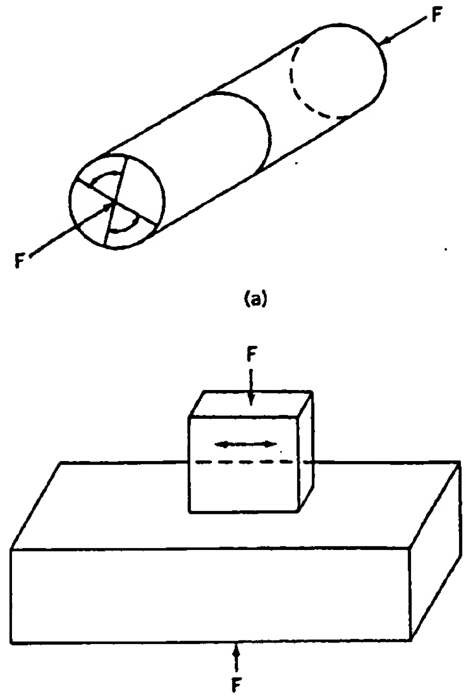


Figure 4.11 Schematic of (a) angular reciprocating friction welding and (b) linear reciprocating friction welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

process is usually called *ultrasonic welding* (*USW*), and is often treated as an entirely different process, although it is not! The only real difference is the amplitude and frequency of motion compared to more conventional friction welding. For conventional friction welding, the amplitude of vibration is relatively large (fractions of to several millimeters) and the frequency is quite low (typically, 10^2–10^3 cycles per second). Ultrasonic vibration scrubs materials together, while under pressure, generates heat, and produces a weld usually without a distinct forging step. As can be seen in Figure 4.13, the ultrasonic energy is provided by a piezoelectric transducer.

There are, in fact, four variations of ultrasonic welding, according to the AWS, based on the type of weld produced: (1) spot, (2) ring, (3) line, and (4) seam. The names are fairly self-descriptive, and the different types are not

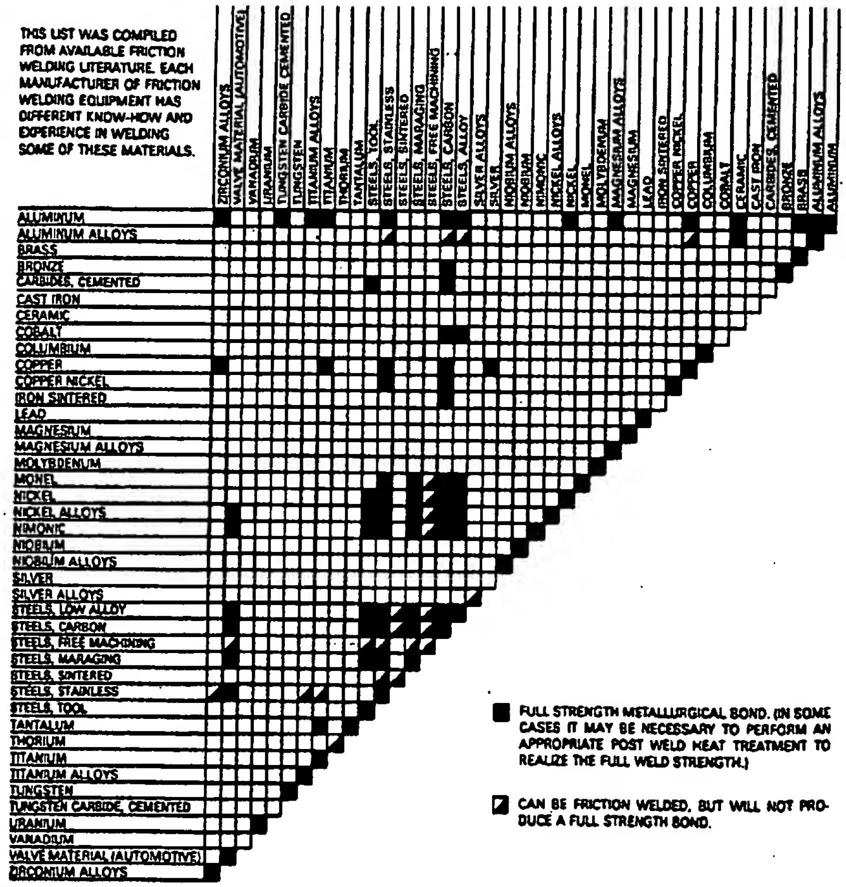


Figure 4.12 Material combinations that can be joined by friction welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

detailed here. These process variations can be used to produce welds in a host of materials, including all thermoplastics and many metals (as shown in Figure 4.14).

Besides the above-mentioned variations, two special forms of ultrasonic welding are used explicitly for spot welding in microelectronic assembly: (1) *microminiature welding* and (2) *microminiature thermosonic welding*. In the former, the only difference compared to conventional ultrasonic welding is the scale of the welds. They are much smaller to allow welding of wires that range

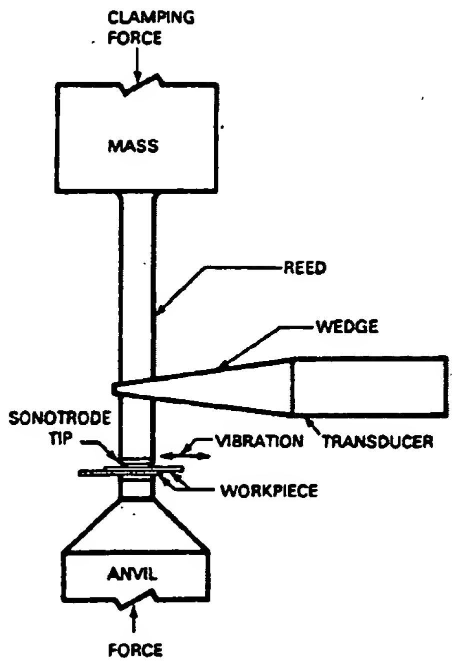


Figure 4.13 Schematic of a wedge–reed ultrasonic spot welding system. Note the piezoelectric transducer used to supply needed vibrational energy to cause frictional heating. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

from 0.001 to 0.020 in. (25 to 500 μm). In the latter, the difference is that the microminiature ultrasonic welding is performed while the substrates are heated to temperatures between 215 and 400°F (100 and 200°C). The belief is that heating facilitates weld formation by both softening the substrates and helping remove any light oxide or tarnish layers that might be present after cleaning. Both of these process variations are often referred to as bonding rather than welding.

4.3.5. Friction Stir Welding

A relatively new variation of friction welding is *friction stir welding*. In this process, primarily developed at The Welding Institute (TWI) in England, a tool or tip is rapidly rotated while being squeezed between two abutting workpieces (as shown schematically in Figure 4.15). The combination of squeezing pressure and rapid rotation (i.e., relative motion between tool and work) leads

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al ALLOYS	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be ALLOYS		●	●			●										●		
Cu ALLOYS			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe ALLOYS						●		●	●	●	●		●	●		●	●	●
Mg ALLOYS							●						●			●		
Mo ALLOYS								●	●		●			●		●	●	●
Ni ALLOYS									●	●	●			●		●	●	
Pd										●			●	●				
Pt ALLOYS											●	●		●		●	●	
Si													●	●				
Ag ALLOYS													●	●				●
Ta ALLOYS														●		●	●	
Sn															●			
Ti ALLOYS																●	●	
W ALLOYS																	●	
Zr ALLOYS																		●

Figure 4.14 Metal combinations that can be ultrasonically welded. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

to frictional heating and softening of the faying surfaces of the workpieces. Melting is a possibility, because the heating can become so intense. Whether melting occurs or the workpiece faying surfaces are just softened, material from each joint member is intermixed or stirred, hence the name. The result is a weld. A distinct advantage of the stir-welding process is that materials that might normally be incompatible if fused can be successfully intermixed and caused to weld.

To make the process work, the depth of tool plunge into the joint, rotational speed, rate of feed or translational motion, and squeezing pressure must all be carefully determined and controlled. As one might expect, there tends to be more heating and deformation or stirring on one side of the joint than on the other, due to the way in which the relative rotational and translational velocities add. Compensation can be made for this effect.

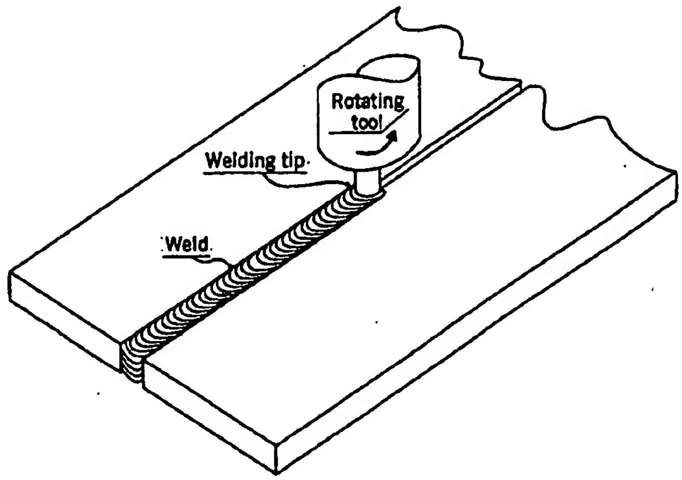


Figure 4.15 Schematic of friction stir welding.

4.3.6. Friction Surfacing

This variation on friction welding uses rotational motion of one part, but at the same time adds a relative motion in a direction perpendicular to the axis of rotation. This process is used to deposit material in a solid state to any of a variety of parts from flat plates to cylinders. The material being deposited comes from one of the parts involved in the process, usually the rotating one (as shown schematically in Figure 4.16) as a consumable, analogous to the way in which colored wax is deposited by a crayon. This material might be used to provide corrosion resistance or wear protection, so the process is really a surfacing process. The thickness that can be deposited is more limited than arc or beam fusion processes.

4.4. DIFFUSION JOINING PROCESSES

As mentioned at the beginning of this chapter and in Section 2.2, it is possible to obtain material continuity and produce a weld using only diffusion of atoms. When such diffusion takes place in the solid state, a weld is produced by what is called *diffusion welding*. When the diffusion process is enhanced or accelerated by the presence of a liquid, even if only in minute quantities for very short times (i.e., is transient), a joint is produced by what is properly called *diffusion brazing*. Both processes are popularly, but not properly, referred to as diffusion bonding.

Each process variation is described below, along with some special variations in which part forming and welding or bonding are accomplished simultaneously.

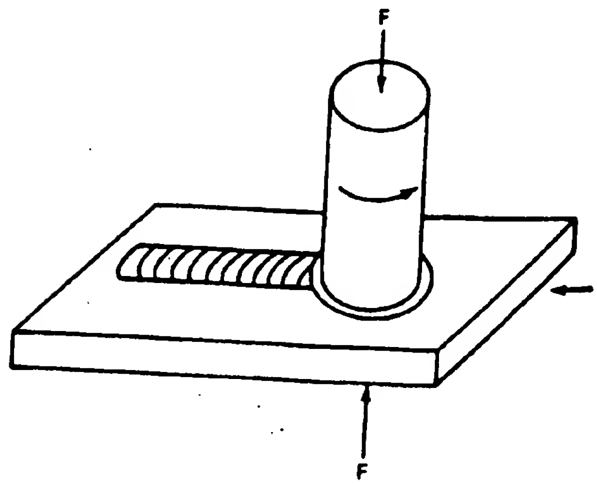


Figure 4.16 Schematic of friction surfacing. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

4.4.1. Diffusion Welding

When properly defined, as by the AWS, "*Diffusion welding* (DFW) is a solid-state welding process that produces a weld by the application of pressure at elevated temperature with no macroscopic deformation or relative motion of the workpieces." A filler metal may or may not be inserted between the faying surfaces to facilitate weld formation by either helping to achieve more points or areas of intimate contact between substrates (through plastic accommodation), or speeding diffusion by providing a faster diffusing atomic species. The process is referred to by a number of other names, including diffusion bonding and solid-state bonding (which are both reasonable); pressure bonding, isostatic bonding, hot press bonding, and hot pressure welding (which are all reasonable, assuming that significant pressure is actually employed); and forge welding (which is usually not accurate, except for a particular variation of pressure welding in which diffusion plays an important role). In reality, diffusion is involved in every welding process, whether fusion or nonfusion, without or with pressure.

The diffusion welding process takes place in several steps as shown schematically in Figure 4.17 and as described in Chapter 2.

Diffusion welding offers some very special and often unique advantages: (1) metals as well as ceramics can be joined directly to form a completely solid-state weld, which has the potential (offered by no other process!) of producing a perfect weld—with a wrought structure, generally free of heat effect; (2) a

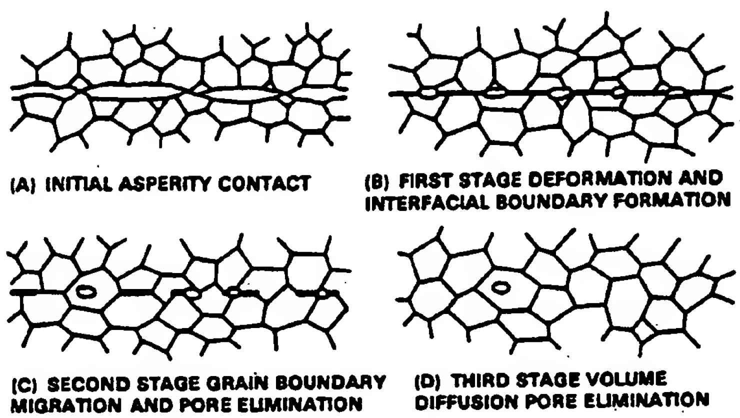


Figure 4.17 Schematic of the three-step mechanistic model of diffusion welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

filler can be used to permit increased microdeformation to provide more contact for bond formation and/or promote more rapid diffusion by providing a faster diffusing species; (3) dissimilar materials either by class or type, including metal-to-ceramic joints, can be joined directly or with the aid of a compatible filler or intermediate; (4) large areas can be bonded or welded, provided uniform intimate contact can be obtained and sustained; and (5) there will be no heat-affected zone as such, since the entire assembly in which the diffusion weld is being made is virtually always heated to the same temperature. (This means that whatever heating to the diffusion welding or bonding temperature does to the microstructure of the joint elements or base materials, it does everywhere! This may not be as bad as a distinct heat-affected zone, because, at least, there is no metallurgical notch. This is true provided, of course, that the change in the microstructure caused by heating is acceptable.)

Among the key parameters of the process—temperature, time, and pressure—temperature is by far the most important, provided there is enough pressure to cause contact between joint elements! The reason temperature is so important is that diffusion occurs by an Arrhenius relationship, that is, exponentially with temperature:

$$D = D_0 e^{-Q/kT} \tag{4.1}$$

where D is the diffusion coefficient (of the diffusing species) at temperature T, D_0 is a constant of proportionality (dependent on the particular diffusing

species and host), Q (or frequently, Q_d) is the activation energy for diffusion to occur, k is Boltzmann's constant, and T is the temperature on an absolute scale (kelvin). In general, diffusion welding begins to take place at a reasonable rate when the temperature exceeds half the absolute melting point of the base or host material(s), and, as a rule-of-thumb, the rate of diffusion doubles every time the temperature is raised approximately 30°C or K (50°F).

Time is important because diffusion takes time to occur, since for atoms to jump from site to site takes time. Thus, the distance over which diffusion occurs depends on time:

$$x = C(Dt)^{1/2} \tag{4.2}$$

where x is the diffusion distance, D is the diffusion coefficient (as above), t is time, and C is a constant for the system.

Pressure is important from several standpoints, depending on which step of the process is considered. Initially, pressure is absolutely critical to establish point-to-point contact across which diffusion can occur; the higher the pressure, the more points and area of contact, so the more diffusion can occur for any particular temperature. Later in the process, pressure can help speed diffusion welding by being high enough to cause creep and/or sufficient plastic deformation that dynamic recrystallization occurs; the greater the deformation, the lower the recrystallization temperature. While certainly of secondary importance, pressure also enhances diffusion through a tension stress gradient concentration that expands the crystal lattice to make atom migration easier.

Besides these important process parameters, there are important metallurgical factors, including allotropic phase transformations (in some metals and alloys) that will speed diffusion both due to plastic accommodation at faying surfaces and faster diffusion as the transformation takes place; any microstructural condition that would tend to modify diffusion rates (e.g., occurrence of recrystallization); and ability to form dissimilar material joints (e.g., ceramic to metal), provided there is sufficient compatibility to allow mutual interdiffusion.

Heating during diffusion welding can be accomplished using a furnace, retort, autoclave, hot-platen press, or by resistance. Pressure can be applied by dead-weight loading, a press, differential gas pressure, or by differential thermal expansion of the parts or of tooling. Uniaxial methods of applying pressure limit welding to flat, parallel, planar surfaces, roughly perpendicular to the direction of load application. Isostatic pressurization, employing encapsulation or "canning," offers better pressure uniformity and is applicable to more complex geometry. (Remember that the principal purpose of applying pressure is to obtain contact at the interface to be joined. This contact initially occurs by plastic deformation of microscopic asperities, and later by creep.) Almost always, diffusion welding is made to take place in a protective, often inert, atmosphere. This is to prevent formation of interfering oxide or other tarnish layers after they have been removed prior to attempting to diffusion weld.

Components to be diffusion welded must be specially designed and carefully processed to produce successful joints consistently. The process is economical only when close dimensional tolerances, expensive materials, or special material properties are involved. Even then, not all metals can be easily diffusion welded or bonded. One excellent example, however, is titanium for aerospace applications. Titanium has the rather unusual characteristic of being able to dissolve its own oxide at a certain temperature (approximately 1000°C or 1800°F). Other metals and alloys that can be diffusion welded are nickel alloys, low-carbon steels, and aluminum alloys, although the persistent oxide associated with aluminum must be dealt with. Dissimilar metal combinations, as well as many combinations of ceramics of similar and dissimilar composition can be diffusion welded. Some ceramics can even be diffusion welded to some metals.

4.4.1.1. *Conventional Diffusion Welding.* What has just been described is what is referred to as *conventional diffusion welding*.

4.4.1.2. *Deformation Diffusion Welding.* There are variations of the diffusion welding process in which the degree of plastic deformation caused by the application of pressure is substantial. When this is the case, the process is often referred to as *deformation diffusion welding*. The impact of the severe plastic deformation is favorable in three ways: (1) Lots of contact is obtained from the outset of the process. (2) Severe plastic deformation is almost certain to break up oxide. This is especially important for materials that inherently form an aggressive and tenacious oxide, such as aluminum and its alloys do. (3) Lots of deformation means recrystallization at much lower temperatures. This will speed the effects of diffusion through new grain formation at and growth across the original interface.

4.4.1.3. *Resistance Diffusion Welding.* There is a variation of diffusion welding that is made to take place through the pressure and heating associated with the resistance spot welding (RSW) or resistance seam welding (RSEW) processes. It is called *resistance diffusion welding*. Other than the means by which heat and pressure are applied, there is no difference from conventional diffusion welding.

4.4.1.4. *Continuous Seam Diffusion Welding.* In *continuous seam diffusion welding* (CSDW), components are joined by yield-controlled diffusion welding. Parts are positioned so that their faying surfaces are properly abutted or overlapped, and then the assembly is passed through tooling consisting of four rollers. The rollers are usually made from molybdenum so that they can apply heat by resistance through the passage of current from the rollers through the parts and joints. The result is a continuous diffusion seam weld, an example of which appears in some built-up structural steel I-beams, where top and bottom members are CSD-welded to the web.

4.4.2. Diffusion Brazing

Diffusion brazing (DFB) is similar to conventional brazing, except that the filler metal and brazing temperature and time are selected so that the joint that results has physical and mechanical properties almost identical to the base metal. To do this, it is necessary to diffuse the braze metal almost completely into the base metal. The most important reason for doing this is to raise the remelt temperature of the joint once it is formed by brazing to well above the brazing temperature. A typical application is the diffusion brazing of nickel-base superalloy blades to an identical-composition disk.

In this process, liquid is formed at the joint interface through a eutectic reaction between the base metal or one of the base metal components and the filler or one of the filler components, as it must be for a process to be considered a brazing process. The liquid is normally quite transient, however, with solidification occasionally occurring isothermally.

4.4.3. Combined Forming and Diffusion Welding

It was found with commercially pure (CP) titanium and many titanium alloys (e.g., two-phase, alpha-beta, Ti-6Al-4V, Ti-6Al-2V-2Sn, and others) that diffusion welds could be made at the same time the material was hot formed. Undoubtedly, this discovery was made accidentally when two parts being formed were found to have welded together! Two process variations exist: (1) *creep isostatic pressing* (CRISP) and (2) *superplastic forming/diffusion welding* (SPF/DFW).

The reason these processes work is that, fortuitously, titanium and many of its alloys exhibit creep and superplasticity in the same temperature range in which they diffusion weld. (Recall that titanium also exhibits the rather unusual characteristic of being able to dissolve its own oxide before it melts, which means it self-cleans faying surfaces, even when tightly abutted.) Thus, while parts are being hot formed either by normal creep or superplastic behavior due to grain boundary sliding between alpha and beta phases, they also diffusion weld. After all, the temperature of both hot forming and diffusion welding is around 1700°F (925°C), which is over $0.50T_m$. Material flow by creep or superplasticity occurs at such low stresses that gas pressure (usually only hundreds of psi or a few MPa) can be used to cause forming, as well as to provide isostatic pressure to cause welding.

The forming and diffusion welding cycles can, in fact, be caused to occur in either order, depending on the particular design and process variation. That is, parts can be caused to diffusion weld and then formed, or formed and then diffusion welded. To prevent diffusion welding where it is not wanted, chemically inert and thermally stable oxides (e.g., yttria) are used as maskants.

Several materials besides titanium and some of its alloys can be made to simultaneously form and diffusion weld. Examples include some aluminum alloys (once specially processed to refine their grain structure considerably),

some nickel-base superalloys, pure copper and some copper alloys, and some ultra-fine-grained steels.

Figure 4.18 shows how SPF/DFW can be made to occur to produce complex shapes from titanium alloys for use in advanced aircraft, including both various possibilities for stabilizing skin structures (a) and replacing traditional design and fabrication techniques using either buildup (rivet-assembly) of details or machining (b).

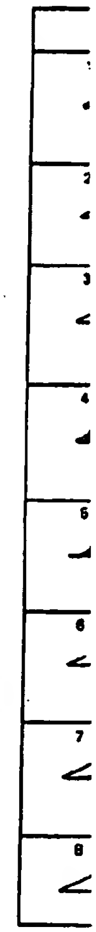
4.5. SOLID-STATE DEPOSITION WELDING PROCESSES

While the underlying processes have been used for a long time, it has only recently been realized that *chemical deposition*, *electrochemical deposition* and *vapor deposition* can be used to weld materials together. These processes are or will be called *solid-state deposition welding processes.* For the most part, chemical bonds are formed as one material is deposited on another because the interface is atomically clean and contact is intimate which are the two requirements for producing a weld (see Chapter 2). Granjon (1991) spoke of this possibility when he wrote about the role of interfaces in causing welding (Section 2.4.4). While there are still only a few real applications, usually on very small scales where the boundary between a material and a structure becomes blurred, the future bodes well for these processes.

4.6. INSPECTION AND REPAIR OF NONFUSION WELDS

Nonfusion welding processes, as a group, pose a special challenge, despite their attractiveness to preserve microstructure and properties. The joints produced by all nonfusion welding processes tend to be thin compared to their fusion-welding counterparts and can involve much greater joint area. This makes nondestructive evaluation inherently difficult, whether by x-radiography, due to the thinness of planar defects relative to the thickness of the assembly, thereby exceeding resolution limits, or by ultrasound, due to the ease with which a significant proportion of sound can be transmitted by many very small connecting paths or ligaments. As if this isn't bad enough, once detected, it is often impossible to repair defects in nonfusion welds. This tends to be true because the joint often involves a large surface area, just because of the capability of such processes to produce such joints!

The designer and the process engineer must know what they are letting themselves in for in the way of inspection and repair when they choose nonfusion over fusion welding approaches. Nothing comes without a cost!



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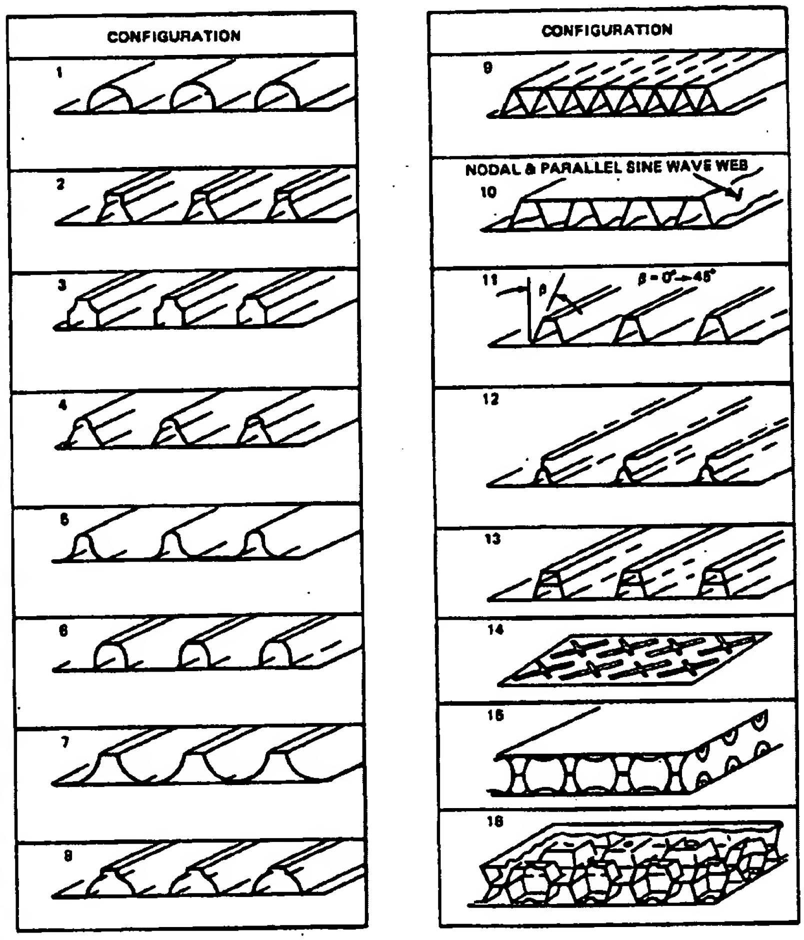
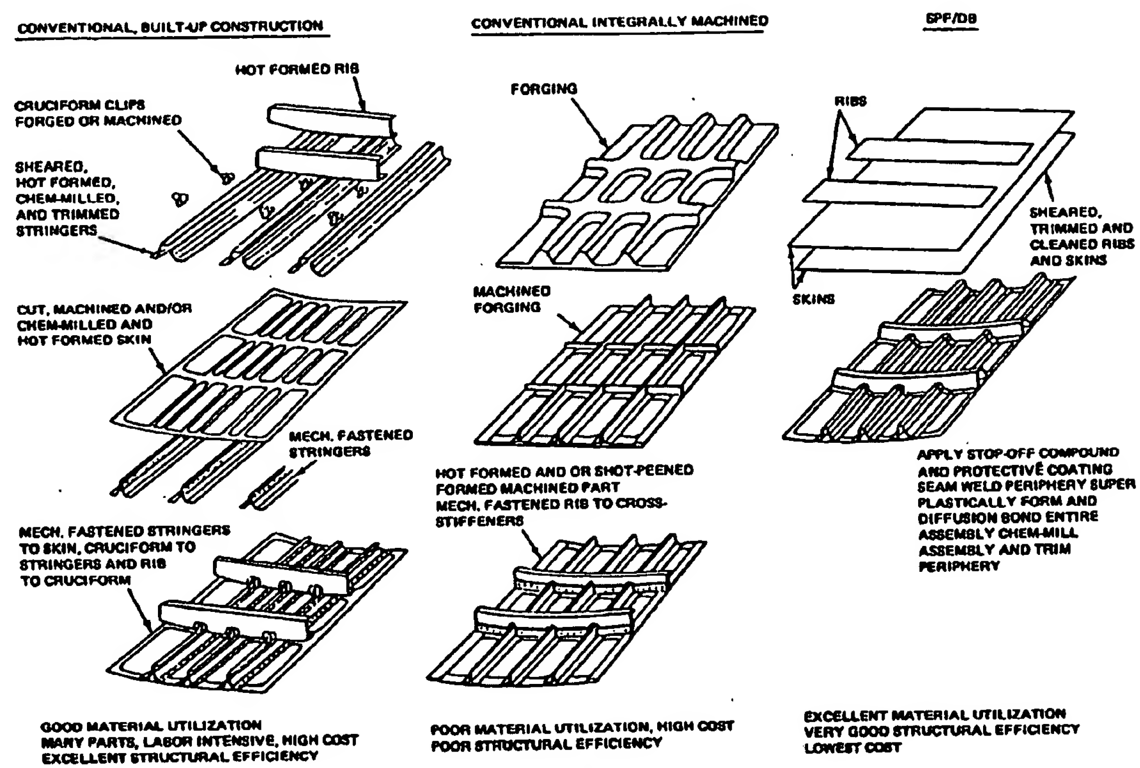


(a)

Figure 4.18a Schematic of superplastic forming/diffusion welding (SPF/DFW) of titanium alloy parts for an advanced aircraft: (a) various skin stabilization configurations made possible by SPF/DB and (b) comparison of conventional buildup or machining and SPF/DB design and fabrication techniques. (After original work by the author in the late 1970s).



(b)

Figure 4.18b Comparison of conventional buildup or machining and SPF/DFW or SPF/DB design and fabrication techniques. (After original work by the author in the late 1970s).

4.7. SUMMARY

Nonfusion welding processes offer a valuable alternative to fusion welding processes, enabling the joining of difficult, often dissimilar, materials to fairly precise tolerances, with little or no heat effect in the base material. Nonfusion welding processes rely on one of four factors to obtain material continuity and form welds: (1) pressure, (2) friction, (3) diffusion, or (4) solid-state deposition and chemical reactions. There are many variations on these basic approaches, yielding more and more specific processes every day. As materials continue to be more highly engineered in terms of chemical composition and microstructure, nonfusion welding processes will become more important and more prominent.

REFERENCES AND SUGGESTED READING

Suggested reading [by process]

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Exploiting Friction Welding Processes, 1979, Abington Publishing, Cambridge, UK. [FRW]. *Explosion Welding*, 1976, Abington, Cambridge, UK. [EXW]

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CHAPTER 3

FUSION WELDING PROCESSES

3.1. GENERAL DESCRIPTION OF FUSION WELDING PROCESSES

In fusion welding processes, part edges or joint faying surfaces (or, for surface overlay, cladding, or hardfacing, the surfaces to be overlaid) are heated to above the melting point for a pure material or above the liquidus for alloys. In this way, atoms from the substrate(s) are brought together in the liquid state to establish material continuity and create large numbers of primary bonds across the interface after solidification has taken place. Sometimes, filler material must also be melted and added to completely fill the joint gap (or for overlaying, etc., to cover the surface). *Fusion welding processes* include all of those processes in which the melting or fusion of portions of the substrate(s), with or without added filler, plays a principal role in the formation of bonds to produce a weld.[1] As shown in Figure 2.2, all fusion welds contain a distinct fusion zone (FZ), as well as heat-affected zones (HAZ) and unaffected base material. In alloys, there is also a partially melted zone (PMZ) between the FZ and HAZ.

The following sections highlight the principal characteristics of the major fusion welding processes (more complete coverage is available in numerous references, including those given at the end of this chapter). These processes include, in order, (1) processes employing a chemical energy source, including (a) gas welding employing a combustible fuel as the source of heat, or (b) an

[1] There are some processes in which some melting or fusion occurs, but the principal mechanism by which material continuity is obtained is plastic deformation under pressure. Any liquid phase formed is largely superfluous, other than for the fact that it serves to clean the surface(s) being welded through a fluxing action.

exothermic reaction between solid (or solid and gaseous) reactants (i.e., an aluminothermic reaction) as the source of heat; (2) processes employing an electric arc as the energy source, including arcs between (a) a nonconsumable electrode as a source of heat, or (b) a consumable electrode, as a source of both heat and filler metal; (3) processes that develop heat by internal resistance or Joule heating of the workpiece, whether as the result of direct current flow through workpieces that are part of a circuit or currents induced in a workpiece by fluctuating electromagnetic fields; and (4) processes that develop heat from a high-intensity radiant energy, often beam, source through the conversion of the kinetic energy of fast-moving particles in that irradiating flux or beam.

Lets begin.

3.2. CHEMICAL FUSION WELDING PROCESSES

Chemical energy stored in a variety of forms can be converted to useful heat. There is a subset of fusion welding processes that develops the heat needed to cause melting by the transfer of energy from an exothermic chemical reaction to the work. These are *chemical fusion welding processes*, and include two major types: (1) those that employ an exothermic chemical reaction involving the combustion of a fuel gas in oxygen, called *oxyfuel gas welding* (or gas welding); (2) those that employ a highly exothermic chemical reaction between solid-phase particulate materials (or solid particles and a gas), generally referred to as *aluminothermic reactions* (or, more narrowly, Thermit welding).

3.2.1. Oxyfuel Gas Welding

In general, *oxyfuel gas welding* (OFW[2]) includes any welding process in which the source of heat for welding is the exothermic chemical combustion of a fuel gas with oxygen. While natural gas/methane, propane, propylene, butane, or other hydrocarbon gases, or even hydrogen, can be used, oxyacetylene welding, which uses acetylene gas as the fuel, is the most commonly used oxyfuel gas welding process due to its high flame temperature (i.e., intense source energy). *Oxyacetylene welding* (OAW) derives the heat needed to cause melting of the substrates and, almost always, filler from two stages of combustion. In the first stage, known as primary combustion, the acetylene fuel gas partially reacts with oxygen provided from a pressurized gas cylinder to form carbon monoxide and hydrogen:

$$C_2H_2 + O_2 \text{ (cylinder)} = 2CO + H_2 \tag{3.1}$$

[2] Throughout this book, wherever possible, the AWS designation and shorthand code for a welding process are used.

This reaction is exothermic and is responsible for about one-third of the total heat generated by the complete combustion of acetylene. The dissociation of acetylene to carbon and hydrogen releases 227 kJ/mol of acetylene at 15°C (50°F), while the partial combustion of the carbon to form carbon monoxide releases 221 kJ/mol of carbon. No combustion of the hydrogen takes place at this stage. The total heat released by the primary reaction is 448 kJ/mole (501 Btu/ft^3) of acetylene.

In the second stage of oxyacetylene or other fuel gas welding, known as secondary combustion, which occurs immediately after the primary combustion, the carbon monoxide resulting from partial combustion of the carbon dissociated from the acetylene (or other fuel gas) reacts further with oxygen, this time from the surrounding air, to form carbon dioxide, while the hydrogen from the primary combustion dissociation of acetylene (or other fuel gas) reacts with oxygen in the air to form water:

$$2CO + O_2\,(\text{air}) = 2CO_2 \tag{3.2}$$

$$H_2 + 0.5O_2\,(\text{air}) = H_2O \tag{3.3}$$

These reactions are also exothermic and are responsible for two-thirds of the total heat generated by burning the dissociation products of the acetylene completely. Burning of hydrogen to produce water vapor releases 242 kJ/mol of hydrogen, while further oxidation of carbon monoxide releases an additional 285 kJ/mol of carbon monoxide, or 570 kJ/mol for the reaction. The total heat released by the second reaction is thus 812 kJ/mol (907 Btu/ft^3) of acetylene.

The actual primary and secondary combustion reactions occur in the gas flame of an oxygen–acetylene torch in two distinct regions, as shown in Figure 3.1a. Primary combustion occurs in an inner cone, while secondary combustion occurs in an outer flame. Although only accounting for one-third of the total heat of the overall combustion reaction (448 kJ/mol out of 1260 kJ/mole), the inner cone tends to be more concentrated in volume, and so is hotter (i.e., the energy is more dense). Thus, the welder tends to work with the tip of the inner cone near the workpiece to cause melting, using the outer flame to provide a degree of shielding of the molten weld metal and hot, newly formed weld by the carbon dioxide, to provide preheating to aid in initial melting and to slow down cooling once the weld has been made (thereby sometimes avoiding adverse postsolidification or heat-affected zone transformations; see Chapters 14 and 16, respectively.

Similar combustion reactions can be written and energy balances performed for other fuel gas mixtures with oxygen, with different amounts of energy being liberated and different flame temperatures being produced for each. Table 3.1 shows the flame temperatures for several common fuel gas–oxygen mixtures. (Determination of flame temperature is nontrivial, and is discussed in Section 8.7.2).

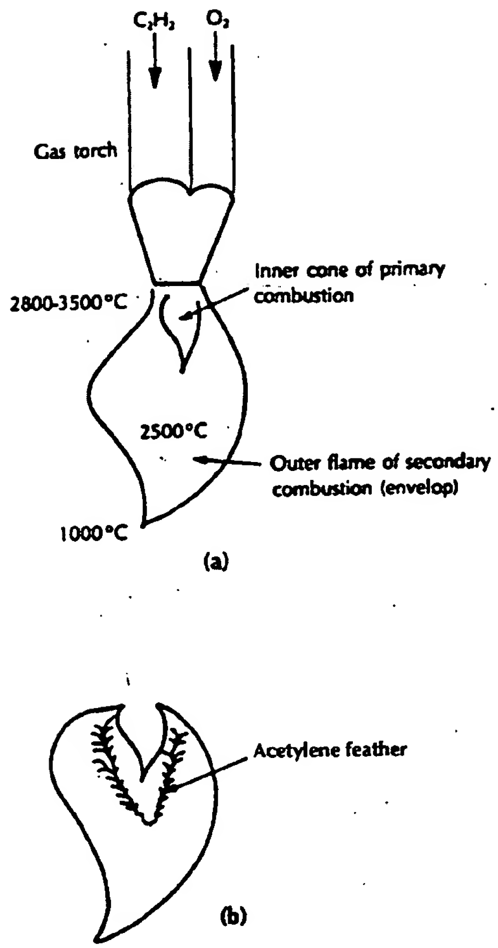

Figure 3.1 Primary and secondary combustion regions in an oxyfuel gas welding flame (a) and the presence of an acetylene feather indicating a reducing flame (b). (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

The exact chemical nature, or reactivity, of the flame in oxyfuel gas welding processes, such as oxyacetylene welding, can be adjusted to be chemically neutral, chemically reducing, or chemically oxidizing. The neutral flame occurs when the molar ratio of acetylene (C_2H_2) to oxygen (O_2) is as it should be in the balanced chemical reaction (e.g., 1:1 in Eq. 2.1). By supplying excess acetylene to the flame, primary combustion becomes incomplete, leaving some

TABLE 3.1 Flame Temperatures and Other Key Features for Various Oxyfuel Gas Welding Processes

Fuel Gas	Formula	Specific Gravity[a] Air = 1	Volume to Weight Ratio[a] ft³/lb	Volume to Weight Ratio[a] m³/kg	Oxygen-to-Fuel Gas Combustion Ratio[b]
Acetylene	C_2H_2	0.906	14.6	0.91	2.5
Propane	C_2H_3	1.52	8.7	0.54	5.0
Methylacetylene-propadiene (MPS)[d]	C_3H_4	1.48	8.9	0.55	4.0
Propylene	C_3H_6	1.48	8.9	0.55	4.5
Natural gas (methanol)	CH_4	0.62	23.6	1.44	2.0
Hydrogen	H_2	0.07	188.7	11.77	0.5

[a]At 60°F (15.6°C).
[b]The volume units of oxygen required to completely burn a unit volume of fuel gas. A portion of the oxygen is obtained from the atmosphere.
[c]The temperature of the neutral flame.

unburned acetylene. The remaining acetylene burns during secondary combustion in the outer flame, producing a tell-tale blue "acetylene feather," as illustrated in Figure 3.1b, and rendering the flame reducing. The neutral flame is attained when the flow of oxygen from the pressurized gas cylinder is increased to the point where the feather just disappears. Increasing the flow of oxygen still further results in an oxidizing flame, where there is actually some oxygen left unreacted in the products.

The reducing flame is good for removing oxides from metals, such as aluminum or magnesium, that are being welded, and for preventing oxidation reactions during welding, such as decarburization (i.e., C to CO_2) in steels. The oxidizing flame causes the metal being welded to form an oxide. This can be useful for preventing the loss of high vapor-pressure components, such as zinc out of brass, through the formation of an impermeable "oxide skin" (here, copper oxide).

All oxyfuel gas flames can be similarly adjusted, and for all, the procedure for lighting and extinguishing the flame is the same. First, the valve on the fuel gas line is opened and the fuel gas is lit with a spark, usually from a flint/steel ignitor. The resulting flame is yellow, "soft," and very sooty. Next, the valve on the oxygen line is opened, at which point the flame becomes very intense and usually white. To achieve final adjustment, the oxygen flow should be reduced until the acetylene feather just appears, at which point the flame is just becoming reducing. Bringing the oxygen flow rate up to just eliminate the feather renders the flame neutral. Further increase or decrease in oxygen flow

TABLE 3.1 (*Continued*)

Flame Temperature for Oxygen[c]		Heat of Combustion					
		Primary		Secondary		Total	
°F	°C	Btu/ft³	MJ/m³	Btu/ft³	MJ/m³	Btu/ft³	MJ/m³
5589	3087	507	19	963	36	1470	55
4579	2526	255	10	2243	94	2498	104
5301	2927	571	21	1889	70	2460	91
5250	2900	438	16	1962	73	2400	89
4600	2538	11	0.4	989	37	1000	37
4820	2660					325	12

[c]May contain significant amounts of saturated hydrocarbons.
Source: Welding Handbook, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of American Welding Society, Miami, FL.

rate from this point renders the flame increasingly more oxidizing or reducing, respectively. To shut the torch off, first the fuel supply and then the oxygen supply is shut off. This is done to prevent the fuel gas from seeking oxygen for combustion when the oxygen valve is closed by tracking up along the oxygen fuel line, to the valve or beyond, and possibly causing an explosion. As an additional safety measure, special check valves or flash-suppressing valves are often used.

The oxyacetylene gas welding process is simple and highly portable. It requires inexpensive equipment, consisting of pressurized cylinders of oxygen and acetylene, gas regulators for controlling pressure and flow rate, a torch for mixing the gases for combustion, and hoses for delivering the gases from the cylinders to the torch. A schematic of a typical torch is shown in Figure 3.2. The process suffers from limited source energy, so welding is slow and total heat input per linear length (see Section 5.4) of weld can be high.[3] Also, the nature of the process limits the amount of protective shielding provided to the weld, so welding of the more reactive metals (e.g., titanium) is generally impossible. To offset this shortcoming, oxyacetylene welding may employ a flux

[3] The heat input per linear length of weld is an important measure of how much thermal distortion or metallurgical transformation (i.e., heat-affected zone) can be expected. The analogy is of running one's finger through a candle flame. Moving quickly causes no burning sensation; but going slowly does—even though the temperature of the candle flame is the same in both instances. Moving faster reduces the heat input. Likewise, welding at high speeds results in a lower heat input per unit length of weld than welding slowly. More is said about heat input in Chapter 5.

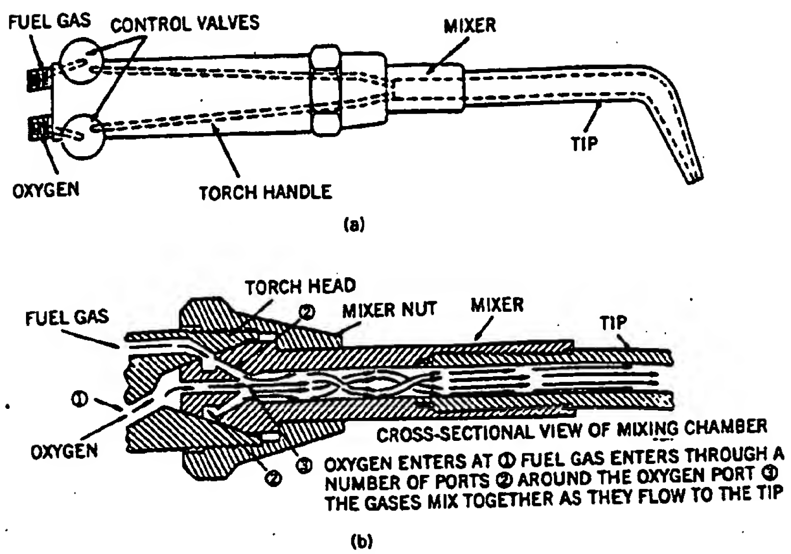

Figure 3.2 Schematic of the basic elements of an oxyfuel gas welding torch (a) and the detail design of a typical gas mixer for a positive-pressure type torch (b). (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA).

or fluxing agent to provide additional protection to the weld, to prevent oxidation during welding, and/or to clean the workpiece of oxide to promote flow and wetting[4] by any filler metal.

Oxyfuel gas welding processes can be used for cutting, gouging (grooving), or piercing (producing holes), as well as for welding. For cutting, gouging, or piercing, the process involves melting the base material and blowing the molten material away with a jet of air or oxygen from a compressed source. Oxyfuel gas processes can also be used for flame straightening or shaping. Torch designs, for the most part, are the same.

3.2.2. Aluminothermic Welding

Aluminothermic welding is commonly known as *Thermit welding* (*TW*).[5] As a subset, these processes use the heat from highly exothermic chemical reactions of solid, particulate materials (or, occasionally, solid particles and a gas) to

[4] Wetting is the phenomenon of a liquid attaching to a solid at a low angle of contact, tending to form a film rather than beads. The more complete the wetting, the smaller the angle of contact, and the more the liquid spreads as a film. The basis for wetting is surface energy reduction.
[5] Thermit is the term commonly used to identify this generic subset of processes, although it is, in reality, a registered trademark referring to a more narrow set of reactions.

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produce melting and joining, also called coalescence, between metals. Most often, the reactants employed are oxides with low heats of formation and metallic reducing agents, which when oxidized have high heats of formation, but combinations of two metals or a metal and a nonmetal (e.g., H, C, O, N, B, Si, S, or Se) that will react exothermically to produce a compound with a high heat of formation can also be used. The excess heat of formation of the reaction products, in either case, provides the energy to produce the weld.

As an example, if finely divided aluminum and metal oxides of, say, iron or copper are blended and ignited by means of an external heat source, the aluminothermic reaction (after which the entire group is named) will proceed according to the following general reaction:

$$\text{Metal oxide} + \text{aluminum} \rightarrow \text{aluminum oxide} + \text{metal} + \text{heat}$$

The reaction is so exothermic that the heat liberated results in the metal formed as a reaction product being liquid. The most common Thermit reactions used to produce welds are

$$\tfrac{3}{4}Fe_3O_4 + 2Al \rightarrow \tfrac{9}{4}Fe + Al_2O_3 \qquad (\Delta H = 838\,\text{kJ/mol of oxide}) \tag{3.4}$$

$$3FeO + 2Al \rightarrow 3Fe + Al_2O_3 \qquad (\Delta H = 880\,\text{kJ/mol of oxide}) \tag{3.5}$$

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 \qquad (\Delta H = 860\,\text{kJ/mol of oxide}) \tag{3.6}$$

$$3CuO + 2Al \rightarrow 3Cu + Al_2O_3 \qquad (\Delta H = 1210\,\text{kJ/mol of oxide}) \tag{3.7}$$

$$3Cu_2O + 2Al \rightarrow 6Cu + Al_2O_3 \qquad (\Delta H = 1060\,\text{kJ/mol of oxide}) \tag{3.8}$$

By causing the reaction to take place such that this molten metal product can reach and fill a joint, a weld can be made. In Thermit welding as it is usually practiced, the reaction is made to take place in a vessel located above a mold around the aligned and abutted joint elements. Once the reaction takes place, the molten metal product, being denser than the solid Al_2O_3 product, pours down into the mold under the influence of gravity and casts into the joint to create a weld. To help the reaction proceed, especially for large volumes of reactant and large welds to be made, the mold is often preheated. A typical arrangement for Thermit welding is shown schematically in Figure 3:3, where concrete reinforcing steel bar is being welded in either a horizontal or vertical orientation. This and the joining of steel railroad rails and heavy copper electric cables or buss bars to terminal connectors are common applications of this process.

While the theoretical maximum temperature that results from such reactions can be calculated from the reaction thermodynamics, the actual maximum temperature achieved is less precise because the reaction does not take place adiabatically. In the case of the most common reaction (given by Eq. 3.4), the

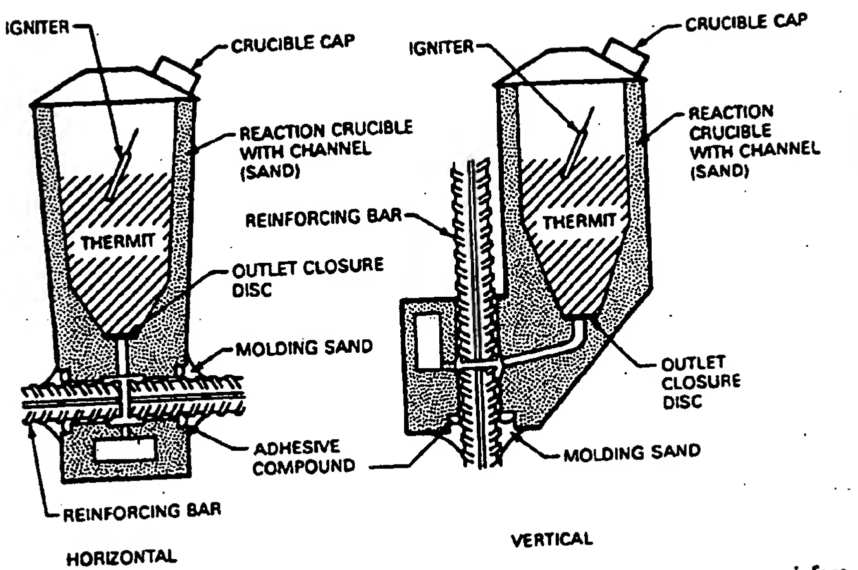


Figure 3.3 Typical arrangement of the Thermit process for welding concrete reinforcing steel bars, horizontally or vertically. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

maximum theoretical temperature is approximately 3200°C (5800°F). Even though the actual maximum temperature probably ranges between 2200°C (4000°F) and 2400°C (4350°F) due to various losses, there is more than enough superheat in the molten metal product to cause melting of the surfaces of the abutting joint elements, thereby producing a real weld.

More recently, as the result of work by Merzhanov et al. (1972) in Russia, a host of exothermic reactions have been studied and used to accomplish surface welding or overlaying by causing the reaction to take place in reactant packed on the surface, and cladding by causing the reaction to take place in reactant sandwiched between layers. Reactions to produce refractory oxides, carbides, nitrides, carbonitrides, borides, silicides, and other nonoxide ceramics as well as intermetallics (e.g., aluminides) have been studied (Hlavacek, 1991) and offer potential to join ceramics to one another and to metals. The former processes are generically classified by the AWS as *exothermic welding* processes, while the latter are classified as *exothermic brazing* processes, the difference being whether any melting of the substrate(s) occurs, as it must to be considered welding. Alternative names for these processes, because of the propagating and simultaneous modes in which the process can take place are: *self-propagating high-temperature synthesis* (SHS) and *combustion synthesis* (CS).

3.3. ELECTRIC ARC WELDING PROCESSES

Energy can be obtained from an electrical or electromagnetic source in three distinct ways: (1) an electric arc; (2) resistance (I^2R or Joule losses) to either the direct flow of current in a circuit or currents induced in the workpiece; and (3) high-intensity radiant energy or beams in which the kinetic energy of particles in the irradiating field or beam is converted to heat by collisions with atoms in the workpiece. Processes relying on each source are discussed in Sections 3.3–3.5.

Fusion welding processes that employ an electric arc as a heat source are called *arc welding processes*. More processes use this source than any other source, primarily because heat for fusion can be effectively generated, concentrated, and controlled. Examples are listed in Table 3.2. The arc in arc welding is created between an electrode and a workpiece or a weldment, each at different polarities. The arc itself consists of thermally emitted electrons and positive ions from this electrode and the workpiece. These electrons and positive ions are accelerated by the potential field (voltage) between the source (one electrode) and the work (the opposite charged electrode), and produce heat when they convert their kinetic energy by collision with the opposite charged element. Although electrons are far less massive than all positive ions (approximately 1/1850th the mass of a proton or positive hydrogen ion), they have much greater kinetic energy because they can be accelerated to much higher velocities under the influence of a given electric field. Since kinetic

TABLE 3.2 Examples of Fusion Arc Welding Processes

Atomic hydrogen (arc) welding	AHW
Carbon arc welding	CAW
Electrogas welding	EGW
Electroslag welding[a]	ESW[a]
Flux-cored arc welding	FCAW
Gas metal arc welding	GMAW
Gas tungsten arc welding	GTAW
Magnetically impelled arc butt welding	MIAB
Plasma arc welding	PAW
Shielded metal arc welding	SMAW
Stud arc welding	SW
Submerged arc welding	SAW

Note: Flash welding and upset welding also involve the establishment of an electric arc, but are classified as resistance, not arc, welding processes.

[a]ESW begins with an arc to heat the flux until it is molten and electrically conductive, at which time subsequent heating arises from the resistance to the passage of current (i.e., Joule heating).

energy is one-half the product of mass and the square of velocity, this is fairly apparent.

The electrode in the above circuit can be intended to be permanent, serving solely as a source of electrons or positive ions, or consumed, in which case it serves both as a source of energy for welding from these particles and as a filler to the weld joint. If the electrode is intended to be permanent, the processes are called permanent electrode arc welding processes or, more commonly, nonconsumable electrode arc welding processes. If the electrode is intended to be consumed, the processes are called consumable electrode arc welding processes.

For nonconsumable electrode arc welding processes, if filler metal is required, it must be added from a supplemental source (e.g., filler wire). Nonconsumable electrodes are usually composed of tungsten or carbon (graphite), because of their very high melting temperatures, but must be protected from oxidation by an inert shielding gas. Consumable electrodes are often composed of the metal or alloy needed in the filler, and come in the form of rods or "sticks" (discontinuous electrodes) or wires (continuous electrodes). They too need to be protected so that the molten metal they produce is not oxidized and contaminated during transfer to the workpiece to produce a weld.

Whether the arc welding process employs a nonconsumable or consumable electrode, shielding must be provided to the weld by a chemically inert or nonoxidizing gas generated by decomposing or dissociating the coating on or flux core in a consumable electrode, or from an external inert gas source (e.g., pressurized gas cylinder) for all nonconsumable and many consumable electrode processes. This shielding is to prevent oxidation of the highly reactive molten weld metal during its transfer to the workpiece to produce the weld, of the newly produced molten weld pool, and of the very hot metal in the just-solidified weld. Shielding gases (from whatever source) also help to stabilize the arc by providing an additional supply of electrons and positive ions.

Several of the more common arc welding processes are described below, nonconsumable electrode processes first, then consumable electrode processes.

3.3.1. Nonconsumable Electrode Arc Welding Processes

There are six predominant arc welding processes that employ nonconsumable electrodes: (1) gas–tungsten arc welding (GTAW), (2) plasma arc welding (PAW), (3) carbon arc welding (CAW), (4) stud arc welding (SW) or arc stud welding, (5) atomic hydrogen welding (AHW), and (6) magnetically impelled arc butt (MIAB) welding. The carbon arc and atomic hydrogen processes are rarely used anymore and the magnetically impelled arc butt process (a rotating arc process as referred to in Section 2.4.4) is practiced rarely outside of Eastern Europe, Ukraine, and Russia, although it has potential. The arc stud process has a highly specialized role for attaching threaded or unthreaded studs to structures using the heat generated by an arc between the stud and the

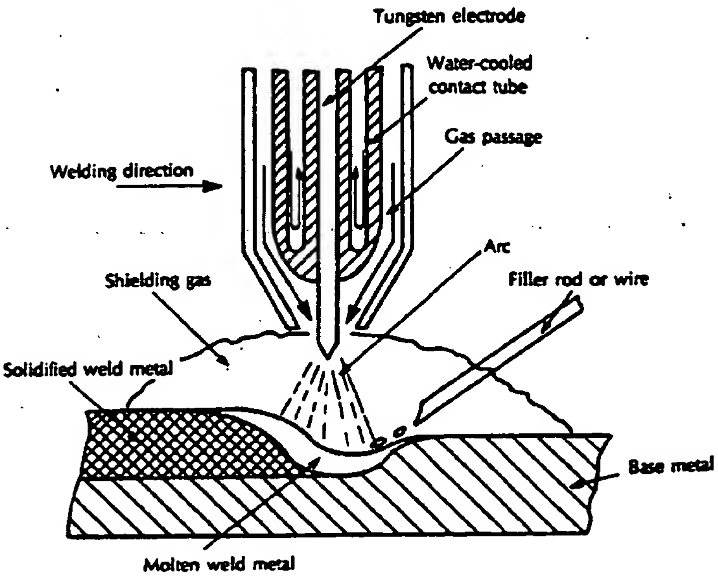


Figure 3.4 Schematic of a gas–tungsten arc welding (GTAW) process, including torch, weld, and electrical hookup. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA).

workpiece and applying a light pressure. These studs are then subsequently used to enable mechanical attachment or fastening (Messler, 1993).

Gas–tungsten arc and plasma arc welding are described in some detail, and the somewhat unusual magnetically impelled arc butt (MIAB) process is described briefly. The other processes are not described at all.

3.3.1.1. Gas–Tungsten Arc Welding. *Gas-tungsten arc welding* (*GTAW*) uses a permanent, nonconsumable tungsten electrode to create an arc to a workpiece. This electrode is shielded by an inert gas, such as argon or helium (or a mixture of the two), to prevent electrode degradation; hence the older, common names tungsten–inert gas (TIG[6]) and heli-arc welding. As shown in Figure 3.4, current from the power supply is passed to the tungsten electrode of a torch through a contact tube. This tube is usually (but may not be) water-cooled to prevent overheating. The gas–tungsten arc welding process can be performed with or without filler (autogenously). When no filler is employed, joints must be thin and have a close-fitting square-butt configuration.

[6] TIG is a trade name of the Linde Company.

The GTAW process, as well as several other arc welding processes to be described later (e.g., SMAW, GMAW, and FCAW), can be operated in several different current modes, including direct current (DC), with the electrode negative (EN) or positive (EP), or alternating current (AC). These different current or power modes result in distinctly different arc and weld characteristics.

When the workpiece or weldment is connected to the positive (+) terminal of a direct current power supply, the operating mode is referred to as direct current straight polarity (DCSP) or direct current electrode negative DC− or DCEN). When the workpiece is connected to the negative terminal of a direct current power supply, the operating mode is referred to as direct current reverse polarity (DCRP) or direct current electrode positive (DC+ or DCEP). In DCSP, electrons are emitted from the tungsten electrode and accelerated to very high speeds and kinetic energies while traveling through the arc. These high-energy electrons collide with the workpiece, give up their kinetic energy, and generate considerable heat in the workpiece. Consequently, DCSP results in deep penetrating, narrow welds, but with higher workpiece heat input. About two-thirds of the net heat available from the arc (after losses from various sources) enters the workpiece. High heat input to the workpiece may or may not be desirable, depending on factors such as required weld penetration, required weld width, workpiece mass, susceptibility to heat-induced defects or degradation, and concern for distortion or residual stress.

In DCRP, on the other hand, the heating effect of the electrons is on the tungsten electrode rather than on the workpiece. Consequently, larger water-cooled electrode holders are required, shallow welds are produced, and workpiece heat input can be kept low. This operating mode is good for welding thin sections or heat-sensitive metals and alloys. This mode also results in a scrubbing action on the workpiece by the large positive ions that strike its surface, removing oxide and cleaning the surface. This mode is thus preferred for welding metals and alloys that oxidize easily, such as aluminum or magnesium.

The DCSP mode is much more common with nonconsumable electrode arc processes than the DCRP mode. There is, however, a third mode, employing alternating current or AC. The AC mode tends to result in some of the characteristics of both of the DC modes, during the corresponding half cycles, but with some bias toward the straight polarity half-cycle due to the greater inertia (i.e., lower mobility) and, thus, greater resistance of large positive ions. During this half-cycle, the current tends to be higher due to the extra emission of electrons from the smaller, hotter electrode versus larger, cooler workpiece. In the AC mode, reasonably good penetration is obtained, along with some oxide cleaning action.

Figure 3.5 summarizes the characteristics of the various current or operating modes of the GTAW process described above. (Incidentally, many of these effects are far less pronounced with other electric arc welding processes employing consumable electrodes. Most particularly, there is little difference in

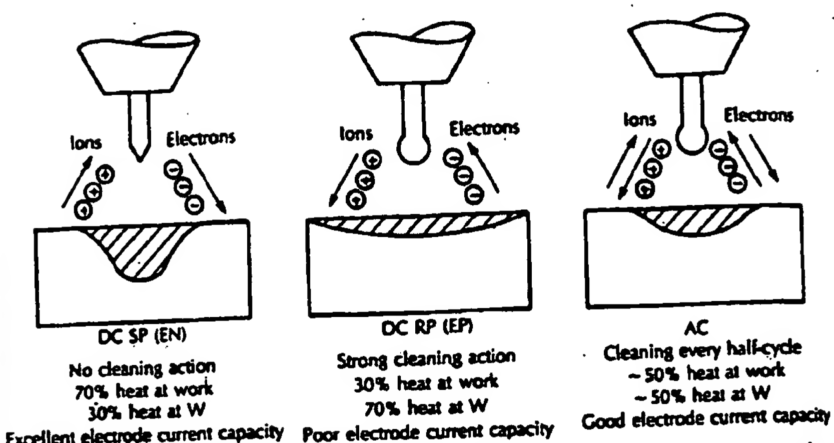


Figure 3.5 Schematic summary of the characteristics of the various operation modes possible for the gas-tungsten arc welding (GTAW) process. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA).

penetration between DCSP and DCRP. This is so since the concentration of heat at the electrode with RP aids in melting the consumable electrode, as is desired, but this heat is returned to the weld when the molten metal droplets transfer to the pool. On the other hand, the cleaning action of the RP mode at the workpiece still takes place.)

In modern welding power supplies designed specifically for GTA welding, there is the added capability for *square-wave* AC and for *wave balancing*. In square-wave AC, solid-state electronic devices reshape the sinusoidal wave provided as input to the power supply from line voltage to give it a square shape; positive for half a cycle and negative for half a cycle. This shape turns out to be advantageous during the transition from one half-cycle to the other, where the voltage and resulting current pass through zero. For normal sinusoidal waveforms, as this transition is taking place, the voltage just before and just after the reversal approaches zero relatively slowly compared to the rate of change for a square wave. The effect of the much more rapid (essentially instantaneous) reversal with a square wave is to avoid possible momentary loss and subsequent difficulty of reestablishing the arc.

In wave balancing, there is the capability of shifting the relative magnitude of the straight and reverse half-cycles, thereby shifting the characteristics of the altered waveform. This is done by applying a DC bias voltage to the AC, whether of sinusoidal or square waveform. The advantage is the ability to fine-tune the waveform for the particular material being welded, obtaining just the degree of straight (penetrating) or reverse (cleaning) half-wave behavior desired. Regardless of mode or waveform, power supplies for GTAW are

generally of a constant current (CC) type. These, as well as constant voltage (CV) and combined characteristic (CC/CV) type supplies, are described in Section 8.2.2.

Square versus normal sinusoidal wave form and wave balancing are shown schematically in Figure 3.6.

The electron emission of tungsten electrodes is occasionally enhanced by adding 1–2% thorium oxide or cerium oxide (or other rare-earth oxides) to the tungsten. This addition improves the current-carrying capacity of the electrode, results in less chance for contamination of the weld by expulsion of tungsten due to localized electrode overheating and melting, and allows for greater arc stability and easier initiation.

As mentioned earlier, both argon and helium are used for shielding with the GTAW process. Argon offers better shielding since it is heavier and tends to stay on the work. Arc initiation is also easier, since the binding energy (i.e., work potential) for electrons in the completely filled outermost electron shell (some of which must be stripped from this shell to provide a conducting

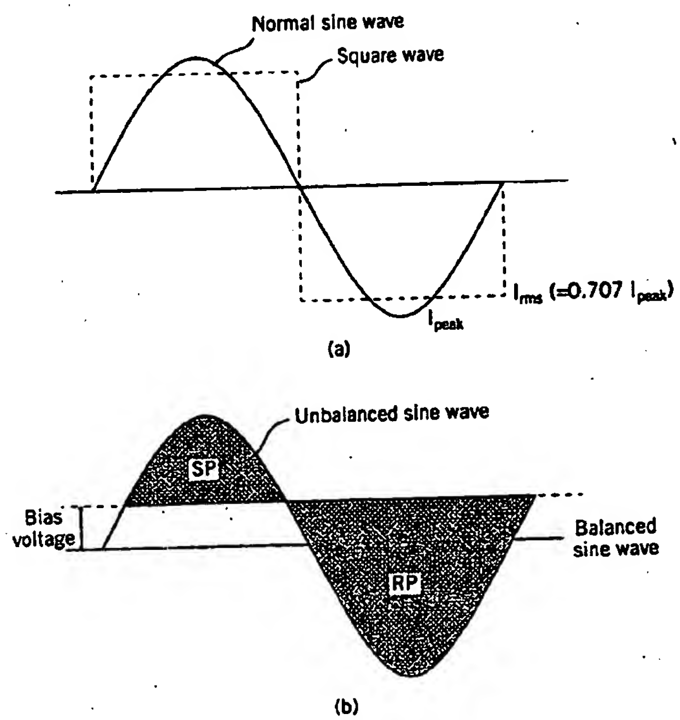


Figure 3.6 Schematic of (a) square versus normal sinusoidal wave AC forms, and (b) wave balancing in the AC operating mode.

plasma) is lower than for helium. The advantage of helium is a hotter arc, which is the result of the higher work potential compared to argon. By using mixtures of these two inert gases, mixed characteristics can be obtained.

In summary, the GTAW process is good for welding thin sections due to its inherently low heat input (especially in the DCRP mode), offers better control of weld filler dilution (see Section 12.1) by the substrate than many other processes (again due to low heat input), and is a very clean process (as a result of the excellent protection afforded by inert argon or helium or argon–helium mixtures). Its greatest limitation is its slow deposition rate (only about 1–2 lbs. or 0.5–1 kg. per hour), although this can be overcome by employing a "hot wire" variation in which the filler wire is resistance heated by being included in the circuit at a lower potential than the electrode. Deposition rate can also be increased to compete with GMAW, SMAW, and FCAW by using much larger, water-cooled electrodes with much higher currents (e.g., upward of a thousand amperes versus around a hundred amperes), or by using a fairly recent variation of the process that employs supplemental flux (*fluxed gas–tungsten arc welding*). In both of these variations, the process must be mechanized, however, to deal with the greater volumes of molten weld metal.

3.3.1.2. Plasma Arc Welding. *Plasma arc welding* (*PAW*) is similar to gas–tungsten arc welding in that it too employs a nonconsumable tungsten electrode to produce an arc to a workpiece. The difference is that in plasma arc welding the converging action of inert gas at an orifice in the nozzle of the welding torch (Figure 3.7) constricts the arc, resulting in several advantages over the GTAW process. These advantages include greater energy concentration (i.e., higher energy density), higher heat content (or source intensity), improved arc stability, deeper penetration capability, higher welding speeds, and, usually, cleaner welds, since the tip of the tungsten electrode cannot accidentally be touched to the workpiece causing contamination. Figure 3.8 schematically shows a comparison of the GTAW and PAW processes.

The plasma in PAW is created by the low-volume flow of argon through the inner orifice of the PAW torch (see Figure 3.7). A high-frequency pilot arc established between the permanent tungsten electrode and the inner nozzle ionizes the orifice gas and ignites the primary arc to the workpiece. When the workpiece is connected electrically to the welding torch such that it is of opposite polarity to the permanent electrode, the plasma is drawn to the workpiece electrically, and the plasma generation is referred to as operating in the transferred arc mode. When the workpiece is not connected electrically to the torch, and the plasma is simply forced to the workpiece by the force of the inert gas, the plasma generation is referred to as operating in the nontransferred mode (see Figure 3.9). The transferred arc mode is usually employed for welding or cutting, while the nontransferred arc mode is usually employed for thermal spraying. Concentric flow of inert gas from an outer gas nozzle provides shielding to the arc and the weld in PAW. This shielding gas can be argon, helium, or argon mixed with helium or hydrogen to obtain subtle differences in arc characteristics.

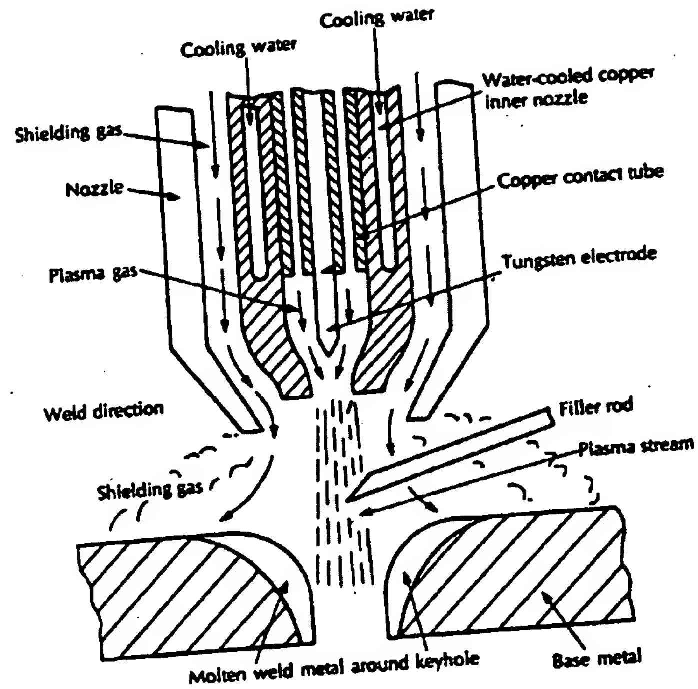


Figure 3.7 Schematic of a plasma arc welding (PAW) torch. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

Two distinctly different welding modes are possible with the plasma arc welding process: the *melt-in* or *conduction mode* and the *keyhole mode*. In the melt-in or conduction mode, heating of the workpiece occurs by conduction of heat from the plasma's contact with the workpiece surface inward. This mode is good for joining thin sections (e.g., 0.025–1.5 mm or 0.001–0.060 in.) and making fine welds at low currents, and for joining thicker sections (e.g., up to 3 mm or 0.125 in.) at high currents. In the keyhole mode, the high energy density of a very high-current plasma vaporizes a cavity through the workpiece and creates a weld by moving the keyhole, analogous to a hot wire through wax. Penetration is great, since the vapor cavity tends to "trap" energy by internal reflection. Molten metal surrounding the vapor cavity is drawn by surface tension or capillary forces to fill the cavity at the trailing edge of the weld. This mode is excellent for welding applications requiring deep penetration, to approximately 20 mm (0.8 in.). These two modes are shown schematically in Figure 3.10. The keyhole mode arises whenever the energy density in the source exceeds a certain level, around 10^9 to 10^{10} W/m^2. It is particularly

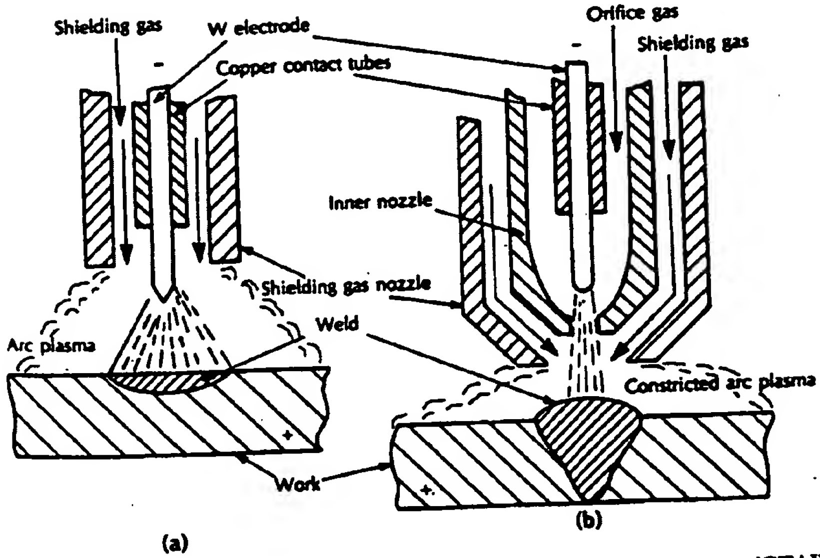


Figure 3.8 Schematic comparison of the (a) the gas–tungsten arc welding (GTAW) and (b) plasma arc welding (PAW) processes. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

important in the high-intensity beam processes discussed in Section 3.5. More traditional, lower-energy-density arc welding processes all operate in the melt-in or conduction mode.

The single greatest disadvantage of plasma arc welding is the required equipment. Power sources, gas controllers, and torches are all more complicated and expensive than for GTAW, and the torches tend to be large, making handling difficult during manual operation.

As for gas–tungsten arc, plasma arc torches can be used with some modification for cutting, gouging, or piercing.

3.3.1.3. Magnetically Impelled Arc Butt Welding. *Magnetically impelled arc butt* (*MIAB*) *welding* (sometimes referred to as rotating arc welding) is a rapid, clean, and reliable arc welding process that employs forging to produce the finished weld. As such, it is classified as an electric arc welding process since that is the energy source for producing melting or fusion, even though pressure from forging is needed to complete the weld. It is thus a fusion arc pressure welding process, and, in that way, is related to arc stud welding, which is not described herein.

The MIAB welding process is well established in Europe (especially Eastern Europe) and the independent states of the former Soviet Union, finding

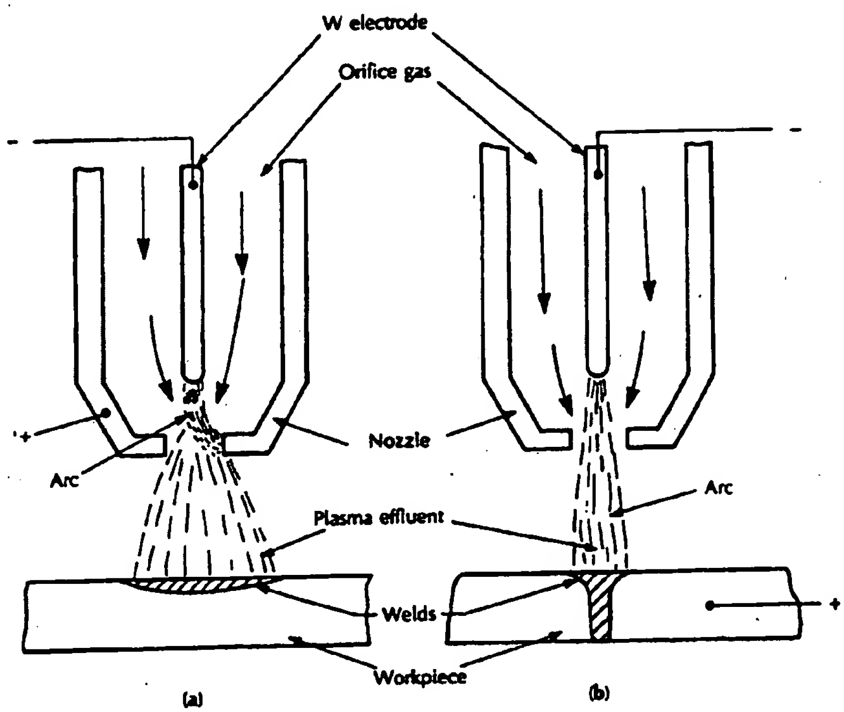


Figure 3.9 Schematic comparison of the (a) nontransferred and (b) transferred arc modes of plasma generation. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

application in the automotive industry for the fabrication of tubular-section butt welds and, to a lesser extent, tube-to-plate welds. Tubes can have circular or noncircular cross sections, with walls ranging from 0.5 to 5 mm or more (0.020 to 0.200 in.) thick. Steel as well as aluminum alloy has been welded successfully in mass production, producing welds with exceptional quality even for safety-critical applications.

In practice, MIAB welding is fully automated. An arc drawn between aligned but properly gapped tube ends is impelled to move (rotate) around the joint line by an interaction of the arc current and an externally applied magnetic field (explained in Section 8.2.1.6), hence the name. Once the arc has heated the ends of the tubes to cause localized melting and adjacent softening in the heat-affected zone, the parts are forged together. This expels most of the molten metal present and a solid-phase bond is formed. The principle of operation is shown schematically in Figure 3.11; typical placement of the magnets used to apply the propelling force to the arc is shown in Figure 3.12.

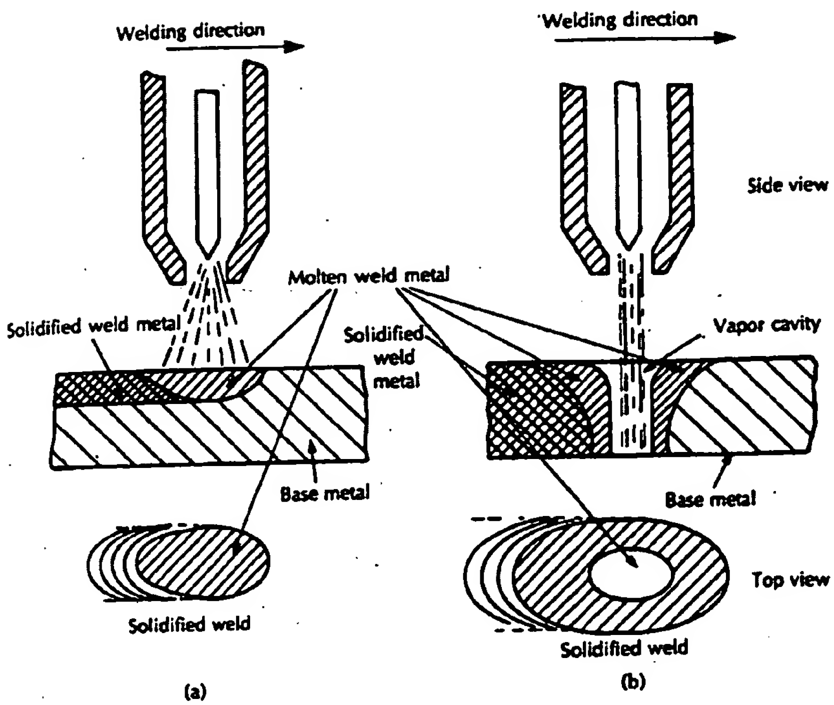


Figure 3.10 Schematic comparison of the (a) melt-in and (b) keyhole modes, exemplified by plasma arc welding (PAW), but found in other high-energy-density processes like electron- and laser-beam welding (EBW and LBW). (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

The major benefits of MIAB welding are (1) no rotation of either component (thereby overcoming problems with asymmetrical parts encountered with many friction welding processes), (2) short welding times (e.g., 2–4 s for 2 to 4-mm [0.040- to 0.080-in.]-thick low-carbon steel tube), (3) low material loss, (4) low fumes and spatter, and (5) relatively low required arc current.

As opposed to flash and upset welding (Section 3.4.2), MIAB welding does not use resistance to accomplish heating at the joint, but, rather, an electric arc. This makes it an arc rather than a resistance welding process. The fact that forging removes most molten metal suggests that the process could be considered nonfusion; after all, the role of the liquid is largely fluxing (as described in Section 11.2.4). The process is considered a nonconsumable electrode arc process because the intent is not to consume the parts being welded and used as electrodes, but to preserve those parts.

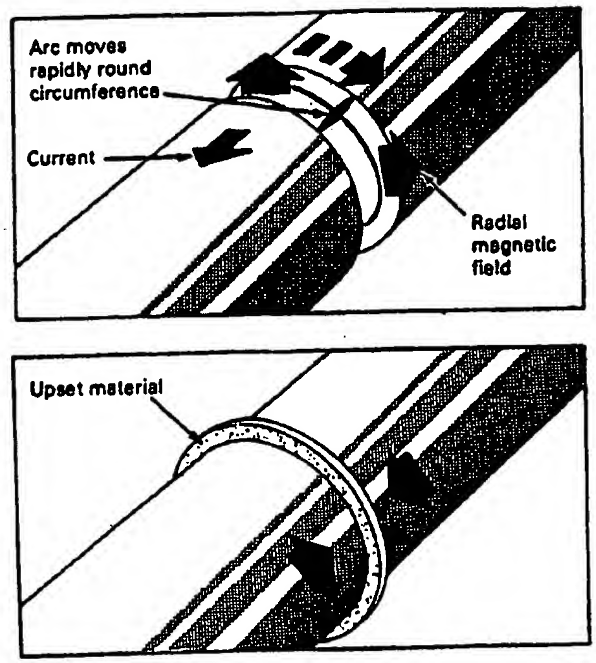


Figure 3.11 Schematic of the operation of the magnetically impelled arc butt (MIAB) welding process. (From "Magnetically Impelled Arc Butt Welding: Development and Applications" by P. Hone, in *Proceedings of Sheet Metal Welding Conference III*, organized and sponsored by the Detroit Section of the American Welding Society, 25–27 October 1988, and used with permission.)

3.3.2. Consumable Electrode Arc Welding Processes

There are six predominant *consumable electrode arc welding processes*: (1) gas–metal arc welding (GMAW), (2) shielded-metal arc welding (SMAW), (3) flux-cored arc welding (FCAW), (4) submerged arc welding (SAW), (5) electrogas welding (EGW), and (6) electroslag welding (ESW). The gas–metal arc and electrogas welding processes employ an inert gas shield provided from an external source, while the shielded-metal and flux-cored arc welding processes achieve shielding from gases generated from within the consumable electrode during melting. The submerged arc and electroslag welding processes achieve shielding of the molten weld metal with a molten slag cover. Each of these processes is described below.

3.3.2.1. Gas-Metal Arc Welding. The *gas–metal arc welding* (*GMAW*) (or metal–inert gas, MIG) process employs a continuous consumable (usually)

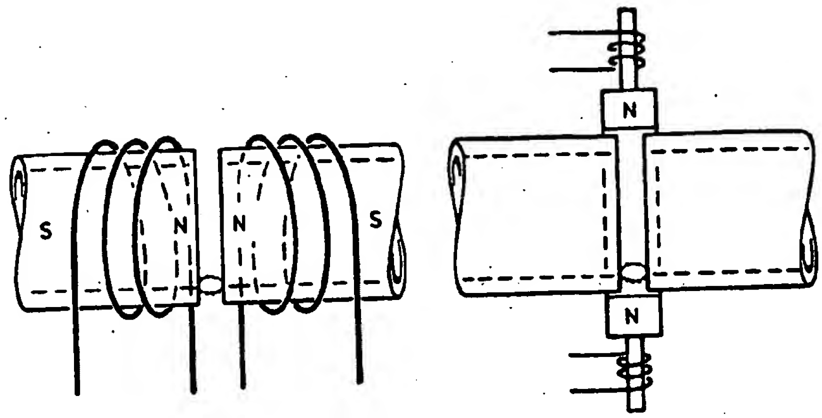


Figure 3.12 Schematic of the typical placement of magnets for propelling the arc in MIAB welding. (From "Magnetically Impelled Arc Butt Welding: Development and Applications" by P. Hone, in *Proceedings of Sheet Metal Welding Conference III*, organized and sponsored by the Detroit Section of the American Welding Society, 25–27 October 1988, and used with permission.)

solid wire electrode and an externally supplied inert shielding gas. A schematic of the process is shown in Figure 3.13. The consumable wire electrode produces an arc with a workpiece made part of the electric circuit and provides filler to the weld joint. The wire is fed to the arc by an automatic wire feeder, of which both push and pull types are employed, depending on the wire composition, diameter, and welding application.

The externally supplied shielding gas plays dual roles in GMAW, as it does in the gas-shielded form of the FCAW and in the EGW processes: First, it protects the arc and the molten or hot, cooling weld metal from air. Second, it provides desired arc characteristics through its effect on ionization. A variety of gases can be used, depending on the reactivity of the metal being welded, the design of the joint, and the specific arc characteristics that are desired.

Constant voltage (CV) DC welding power supplies can be used, hooked up as shown in Figure 3.13. Either DCSP (DCEN) or DCRP (DCEP) may be used, depending on the particular wire and desired mode of molten metal transfer, but the DCRP (DCEP) mode is far more common. The reason is that in the RP mode, electrons from the negative workpiece strike the positive wire to give up their kinetic energy in the form of heat to melt and consume the wire. As opposed to GTAW, in GMAW the heat given up to the wire to melt it is recovered to help make the weld when the molten metal from the wire is transferred to the workpiece.

A distinct advantage of GMAW is that the mode of molten metal transfer from the consumable wire electrode can be intentionally changed and control-

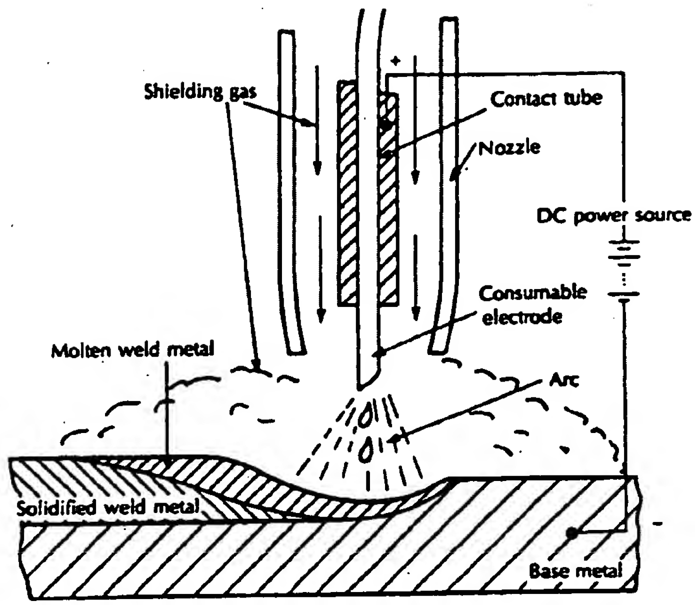


Figure 3.13 Schematic of the gas–metal arc welding (GMAW) process showing torch, weld and electrical hookup (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

led through a combination of shielding gas composition, power source type, electrode type and form, arc current and voltage, and wire feed rate. There are three predominant metal transfer modes: spray, globular, and short-circuiting. There is also a pulsed current or pulsed arc mode, which is not specifically related to the molten metal transfer mode. (More is said about these various modes in Chapter 10.)

The spray transfer mode is characterized by an axial transfer of fine, discrete molten particles or droplets from the consumable electrode to the work at rates of several hundred per second. The metal transfer is very stable, directional, and essentially free of spatter.[7] Spray transfer is produced by welding in the direct current electrode positive (i.e., DC+) mode at high voltages and amperages above some critical value related to the electrode diameter. Argon or argon–helium mixtures are usually employed when welding reactive metals

[7] Spatter refers to molten metal from the consumable (filler wire) electrode that fails to be captured by the weld pool, and runs away to stick on the workpiece surface or drop to the ground. Since spatter represents lost energy and mass, it is undesirable. Furthermore, it is often necessary to remove spatter that has adhered to the workpiece surface (by chipping or machining) for cosmetic reasons, for fit, or so as not to degrade fatigue resistance.

like aluminum, titanium, and magnesium, while small amounts of carbon dioxide (20%) or oxygen (2%) are usually added when welding ferrous alloys to stabilize the arc and give the weld a better and more regular contour.[8] The high arc energy and heat associated with the spray transfer mode limits the effectiveness for joining sheet-gage metals, but the strong directional spray can be useful for welding out of position (i.e., in a vertical plane horizontally or vertically up or down, or in a horizontal plane overhead).

Globular transfer is characterized by large globules of molten metal formed at the tip of the consumable electrode and then released and carried to the workpiece predominantly by gravity and, to a lesser extent, by arc forces including Lorentz pinching and friction. The rate of droplet transfer is slow, typically around 1 to 10 droplets per second. Spatter is usually considerable compared to spray transfer. When argon or argon–helium is used as for shielding, welding currents must be kept low to achieve this mode. Carbon dioxide-rich gases are usually employed when this mode is desired.

Unlike the spray and globular modes, which are known as free-flight modes, in the short-circuiting mode, welding currents and voltages are kept low and the slow-forming molten globules at the end of the consumable electrode are periodically touched to the weld puddle, bridging the electrode–workpiece gap, to cause their release through surface tension forces. This short-circuiting occurs at rates in excess of 50 per second, but requires special power sources. The low currents required for this mode enable the welding of thin sections without melt-through or overwelding. Out-of-position welding is facilitated by the direct transfer of the molten metal through contact. If done properly (i.e., at proper settings of voltage and wire feed speed) spatter is minimized with this transfer mode. The bridging described leads to the alternate classification of the short-circuiting mode as bridging mode transfer.

Rather than employing constant currents during welding, as is usually the case, it is possible to superimpose intermittent, high-amplitude pulses on a low-level steady current that maintains the arc. This is known as the pulsed current or pulsed arc mode. Here, "mode" refers to the mode of current and not the mode of molten metal transfer. This technique allows spray transfer to be obtained at appreciably reduced current levels, during the high-amplitude pulses. Argon-rich gases are essential, and programmable power sources are required, but several advantages are obtained. Relatively large-diameter wires can be used to weld either thin or thick sections, in or out of position.[9]

The globular, short-circuit, and pulsed-arc transfer modes usually employ the direct current electrode negative (DC−) operating mode, while the spray transfer mode usually employs the electrode positive (DC+) operating mode. A schematic of the various major metal transfer modes is shown in Figure 3.14. More will be said about molten metal transfer in Chapter 10.

[8] The contour of a weld refers to the shape of its top bead or crown bead.

[9] Out-of-position welding refers to welding in a position other than with the workpiece in a horizontal plane and the weld deposit being made from above and using the force of gravity to assist in molten metal transfer, which is referred to as in-position.

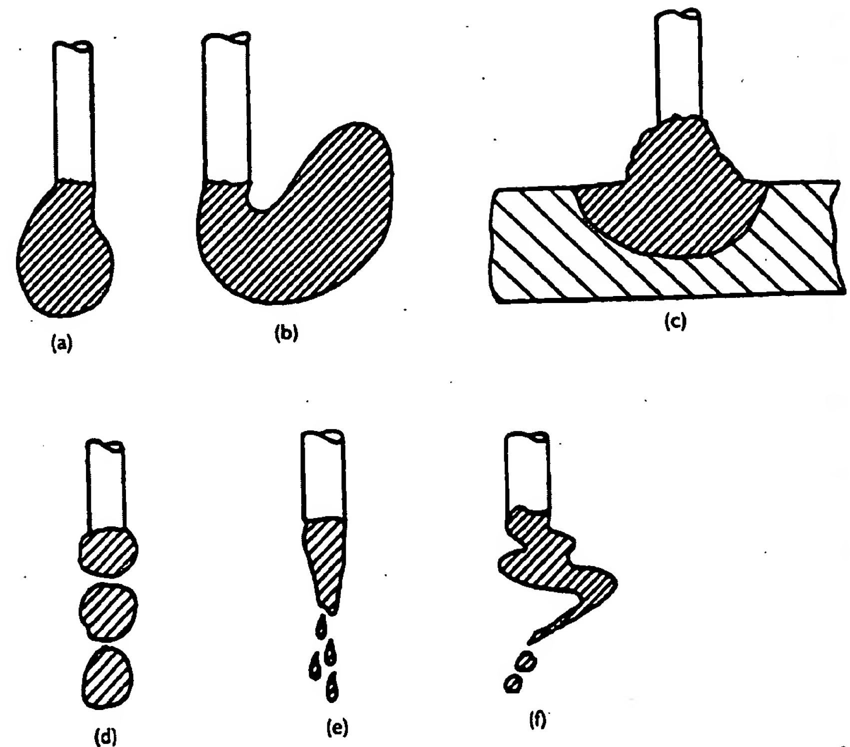


Figure 3.14 Schematic of the predominant modes of molten metal transfer in the gas–metal arc welding (GMAW) process: (a) drop globular, (b) repelled globular, (c) short-circuiting, (d) projected spray, (e) streaming spray, and (f) rotating spray. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

In summary, the GMAW process offers flexibility and versatility, is readily automated, requires less manipulative skill than SMAW, and enables high deposition rates (5–20 kg or 10–40 lb per hour) and efficiencies[10] (80–90%). The greatest shortcoming of the process is that the power supplies[11] typically required are expensive.

3.3.2.2. Shielded-Metal Arc Welding. The *shielded metal arc welding* (*SMAW*) process is also known as the stick welding process. As shown in Figure 3.15, metal coalescence is produced by the heat from an electric arc that

[10] Efficiency, in this case, refers to the efficiency with which energy is transferred from the heat source (here, a torch) to the workpiece for use in making the weld (see Section 5.6).

[11] Constant-voltage (CV) power supplies are employed. These and constant-current (CC) types are described in various references (given at the end of this chapter), and in Section 8.2.2, but not here.

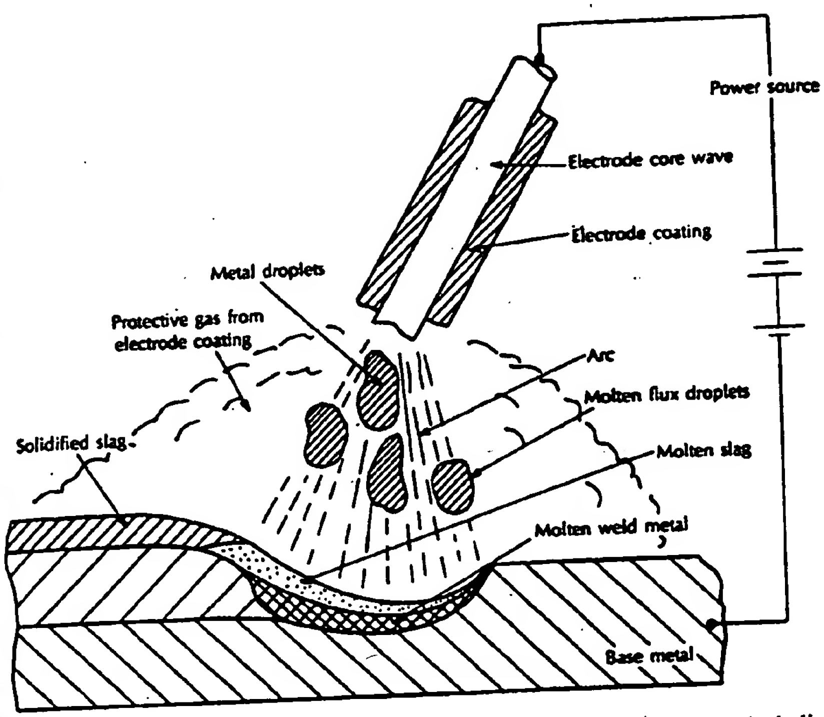


Figure 3.15 Schematic of the shielded-metal arc welding (SMAW) process, including electrode holder and electrode, weld, and electrical hookup (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

is maintained between the tip of flux-coated (or "coated" or "covered"), discontinuous consumable (or "stick") electrode and the surface of the base metal being welded. A core wire conducts the electric current from a constant-current power supply to the arc and provides most of the filler metal to the joint. Some portion of the arc heat is lost to the electrode by conduction, and some source power is lost as I^2R heat.

The covering, coating, or flux on an SMAW electrode, or, later, in the core of an FCAW wire, performs many functions. First, it provides a gaseous shield to protect the molten metal of the weld from the air. This shielding gas is generated by either the decomposition or dissociation of the coating, which may be of several types: cellulosic, which generates H_2, CO, H_2O and CO_2; rutile (TiO_2), which generates up to 40% H_2; or limestone ($CaCO_3$), which generates CO_2 and CaO slag and little or no H_2. The latter type is thus known as a low-hydrogen coating. For cellulosic coatings, gas generation is by thermal decomposition; for rutile and limestone, gas generation is by dissociation. The

different types are selected for different applications, where hydrogen can or cannot be tolerated.[12]

The second thing a coating does is provide deoxidizers and fluxing or reducing agents as molten metal compounds to deoxidize or denitrify and cleanse the molten weld metal, as in metallurgical refining. Once solidified, the slag that is formed from the flux protects the already solidified, but still hot and reactive, weld metal from oxidation. It also aids out-of-position welding by providing a shell or mold in which molten weld metal can solidify.

The third thing a coating does is provide arc stabilizers in the form of readily ionized compounds (e.g., potassium oxalate or lithium carbonate) to help initiate the arc and keep the arc steady and stable by helping to conduct current by providing a source of ions and electrons.

Finally, the coating can provide alloying elements or grain refiners and/or metal fillers to the weld. The former help achieve and control the composition and/or microstructure of the weld (adding to the composition of the core wire), while the latter increase the rate of deposition of filler metal (adding to the metal from the core wire). Both of these offer advantages in electrode manufacturing.

SMAW can operate with both direct current (DC) power supplies, with the electrode positive or negative, or alternating current (AC) power supplies, depending on coating design. Typically, currents range from 50 to 300 A, largely based on electrode diameter, at 10–30 V, resulting in 1- to 10-kg (2- to 20-lb) per hour deposition rates.

Advantages of SMAW are that it is simple, portable, and requires inexpensive equipment (power supply, electrode holder, and cables). The process is versatile, enabling joining and coating or overlaying for restoring dimensions or enhancing wear resistance (hardfacing or wear facing) for fabrication, assembly, maintenance, or repair, in-plant or in the field. Shortcomings of the process are that it offers only limited shielding protection compared to inert gas shielded processes, provides limited deposition rates compared to many other arc welding processes, and is usually performed manually, rather than automatically. Like all manual processes, but even more than most, SMAW requires fair operator skill for best results.

3.3.2.3. Flux-Cored Arc Welding. *Flux-cored arc welding* (*FCAW*) or *open-arc welding* is similar to SMAW in that it is self-shielding; however, the gas- and flux-generating flux is contained in the core of a roll-formed and/or drawn tubular wire, rather than on the outside of a core wire as a coating. The cored wire serves as a continuous consumable electrode, with the filler in the core fulfilling the same functions as the coating in SMAW—providing self-shielding gases, slagging ingredients, arc stabilizers, and alloy additions and deposition rate enhancers. The self-shielding provided by the generation of gases from the core through the arc is more effective than when gas is generated from an external coating. By the time gas that is generated (usually by dissociation of

[12] Hydrogen-generating types of coatings should be avoided when hardenable (i.e., martensite-forming) steels are being welded to avoid hydrogen embrittlement. Martensite formation and hydrogen embrittlement are discussed in Chapter 16.

some core ingredient) reaches the air to be swept away, it has fulfilled its shielding function. For this reason FCAW is an excellent choice for welding in the field, and it is here that it got the name open arc welding.

The FCAW process can also be operated in a gas-shielded mode, in which case it is closely related to the gas–metal arc welding (GMAW) process. Both employ a continuous consumable electrode, both provide filler, and both use an externally provided gas to shield the arc and the weld metal. In either mode (with or without gas shielding), FCAW can be operated with DC power supplies, with the electrode positive or negative, depending on the particular wire type and formulation.

Figure 3.16 shows the self-shielded and gas-shielded forms of FCAW. Process advantages include high deposition rates (e.g., 2–15 kg or 10–30 lb per hour), with actual rates being high due to the continuous operation at higher currents than SMAW; larger, better contoured welds than SMAW; portability; and excellent suitability for use in the field.

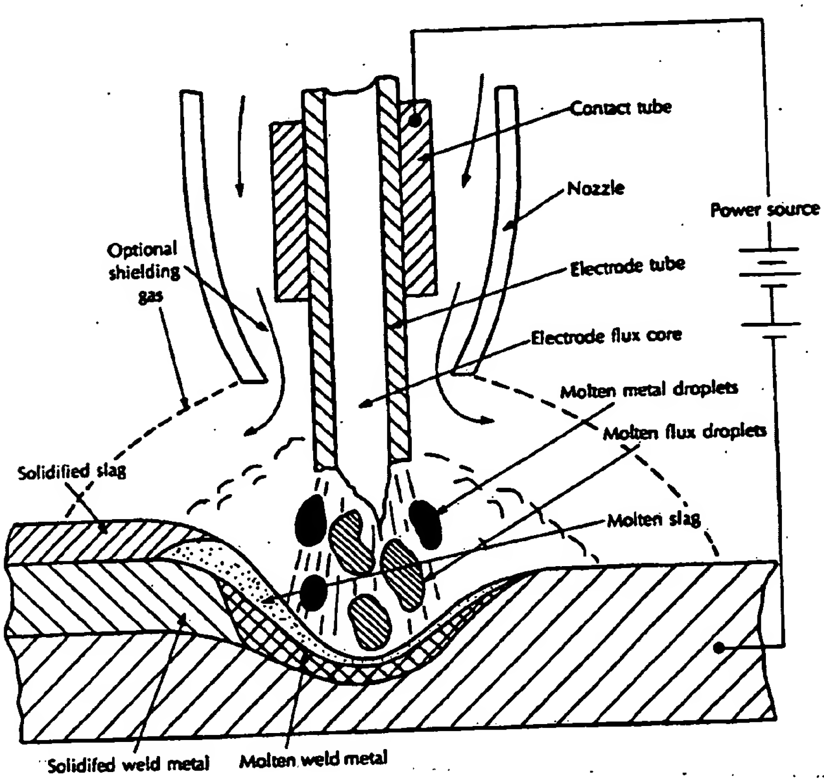


Figure 3.16 Schematic of the self-shielded and gas-shielded forms of the flux-cored arc welding (FCAW) process, including torch and wire, weld, and electrical hookup (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

3.3.2.4. Submerged Arc Welding. In the *submerged arc welding* (*SAW*) process, shown in Figure 3.17, the arc and the molten weld metal are shielded by a covering envelope of molten flux and a layer of unfused granular flux particles. Since the arc is literally buried (or submerged) in the flux, it is not visible. As a result, the process is relatively free of the intense radiation of heat and light typical of most open arc welding processes (e.g., GMAW, SMAW, and FCAW), and resulting welds are very clean. The SAW process employs a continuous solid wire electrode that is consumed to produce filler. The efficiency of transfer of energy from the electrode source to the workpiece is very high (usually over 90%), since losses from radiation, convection, and spatter are minimal (see Sections 5.5 and 5.6).

The sub-arc process is always mechanized, because currents are very high (500 to over 2000 A), deposition rate is very high (27–45 kg or 60–100 lb per hour), and reliability is high. Also, the process must be controlled without relying on feedback of visible signs from the arc, which is so important to the other open arc processes. Thin sections can be welded at very high velocities (up to 500 cm or 200 in. per minute), while very thick sections can be welded at lower velocities, even in the direct current electrode positive (or DCRP) operating mode. At very high currents (over 1000 A), AC is often used to avoid problems with arc blow.[13] The process can be operated with multiple wires or with strip electrodes to further increase deposition rate (the latter occasionally is called strip welding, but this name is applied elsewhere, especially hard surfacing). Welding is restricted to flat and horizontal positions, because of the effects of gravity on the large molten puddles that typify the process, however,

[13] Arc blow refers to the deflection of an arc by the induced electromagnetic fields in conductive materials. It can occur for any arc welding process, and is discussed in more detail in Chapter 8.

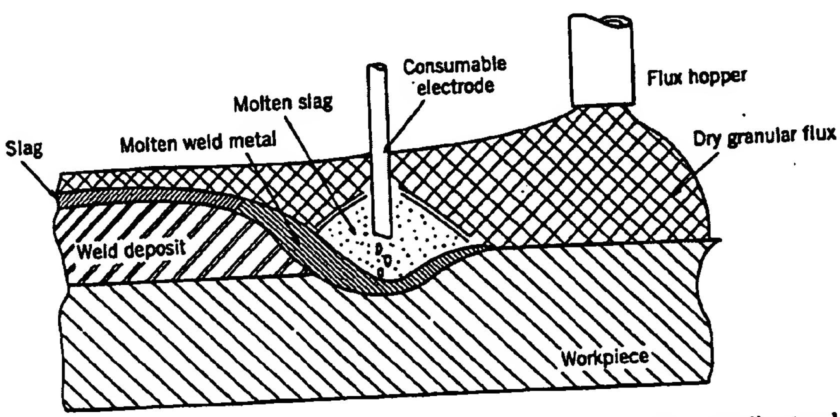


Figure 3.17 Schematic of the submerged arc welding (SAW) process, including torch, weld, and flux hopper. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

a variant of the process at the world-renowned E.O. Paton Electric Welding Institute in Kiev, Ukraine, allows overhead welding. As already mentioned, the inability to observe the puddle directly can hinder control.

The granular flux employed in the SAW process is specially formulated, often containing additives to compensate for the loss of volatile alloying elements (such as chromium) from the filler. Approximately one kilogram of flux is consumed for every kilogram of filler deposited.

3.3.2.5. Electrogas Welding. The *electrogas welding* (*EGW*) process is a heavy-deposition-rate arc welding process, even more so than SAW. The process operates under an inert gas shield provided to a joint enclosed with water-cooled dams, shoes or backing plates, as shown in Figure 3.18. Deposition rate can be as high or higher than SAW, and the quality of weld deposit is excellent, due to the extremely effective shielding provided by the inert gas

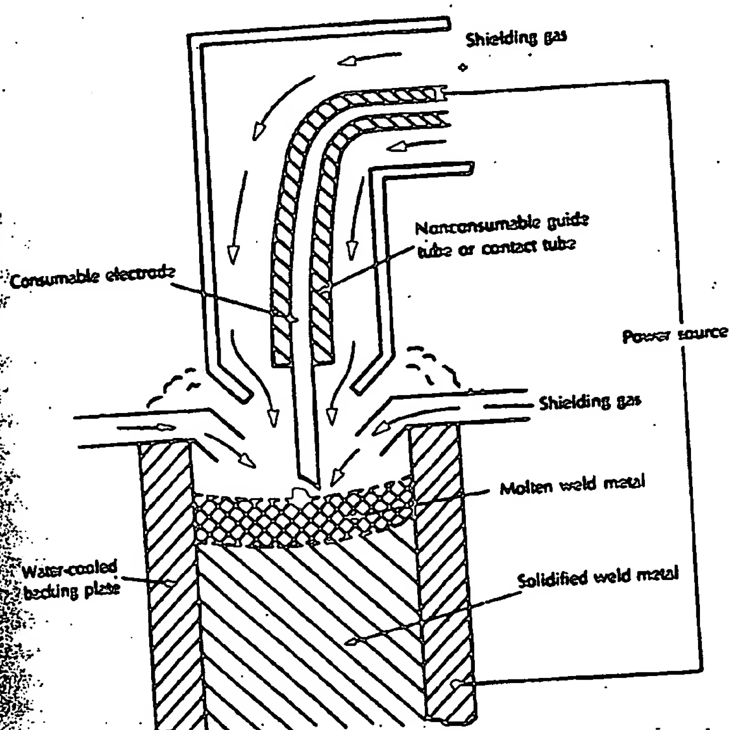


Figure 3.18 Schematic of the electrogas welding (EGW) process, including torch, weld, mold, and electrical hookup. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

coverage. A drawback is that the process can be employed only for welding vertically up, but, in this mode, requires little joint preparation for fit-up.

3.3.2.6. Electroslag Welding. The *electroslag welding* (*ESW*) process is not a true arc welding process. The energy for melting the base metal and filler is provided by a molten bath of slag that is resistance heated by the welding current. An arc is employed only to melt the flux initially, after being struck at the bottom of the joint. Welds are produced in the vertical up direction (and, occasionally, in horizontal fillets), with the joint edges being melted and fused by molten weld filler metal contained in the joint by water-cooled dams or shoes, as shown in Figure 3.19. The molten flux or slag provides excellent

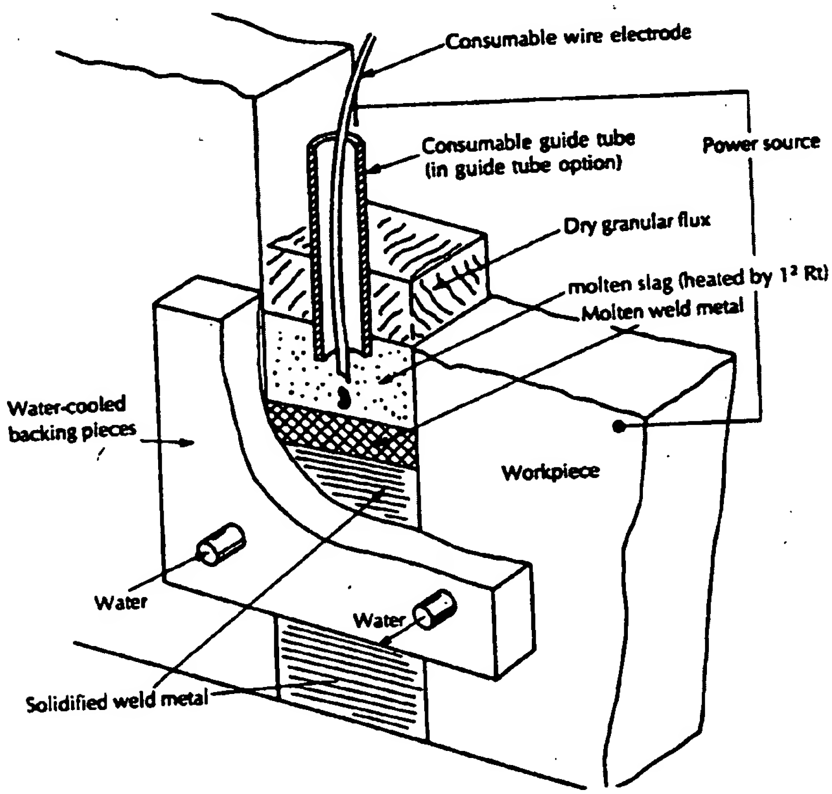


Figure 3.19 Schematic of the electroslag welding (ESW) process, including torch, weld, weld mold, and electrical hookup (From *Joining of Advanced Materials* by R. W. Messler, Jr., Figure 6.22, page 215, published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

protection to the weld. Deposition rates are typically 7–13 kg (or 15–30 lb) per hour per electrode, and multiple electrodes can be employed. In the guide tube mode of this process, a consumable, thick-walled tube is employed to provide additional filler and guide the continuous wire to the bottom of the joint. Here, deposition rate can easily reach 15–25 kg (35–55 lbs) per hour per electrode/guide tube.

Neither electrogas nor electroslag welding is very widely practiced in the United States, although both are practiced elsewhere, especially in the former Soviet states.

3.4. RESISTANCE WELDING PROCESSES

As a group, *resistance welding* (*RW*) processes generate heat through the resistance to the flow of electric current in parts being welded. The parts are usually an integral part of the electrical circuit, with heat generation and welding taking place at the points of contact. Some processes also rely on resistance heating, but in this case internally as the result of field-induced currents. All are called resistance welding processes, however.

As shown in Figure 3.20, contact resistance, especially at faying surfaces, heats the area locally by I^2R or Joule heating, resulting in melting and the formation of a nugget. For the process to work properly, the contact resistance must be higher at the point to be welded than anywhere else. Pairs of water-cooled electrodes, made of copper or copper alloyed with refractory metals to improve erosion resistance, conduct current to the joint, apply pressure by clamping to improve contact (i.e., reduce the contact resistance) at the electrode-to-workpiece interface, and help contain the molten metal in the nugget. The electrical hookup is shown in Figure 3.21. The principal process variables are welding current (usually several thousands to tens of thousands of amperes), welding time (of the order of $\frac{1}{4}$ s), electrode force, and electrode shape. Such DC power to the weld is provided from either single-phase or three-phase AC line voltages of 440–480 V using step-down transformer/rectifiers, for example (see Section 8.4.3). Usually, the process is used to join overlapping sheets or plates as lap joints, which may have different thicknesses.

At least six major types of processes rely on direct resistance heating to produce welds, with several variations within certain types: (1) resistance spot welding (RSW); (2) resistance seam welding (RSEW), employing high frequency (RSEW-HF) or induction (RSEW-I); (3) projection welding (PW); (4) flash welding (FW); (5) upset welding (UW), employing high frequency (UW-HF) or induction (UW-I); and (6) percussion welding (PEW).

3.4.1. Resistance Spot, Resistance Seam, and Projection Welding

Resistance spot welding (RSW) consists of a series of discrete nuggets produced by resistance heating. Nuggets or welds are usually produced directly under the

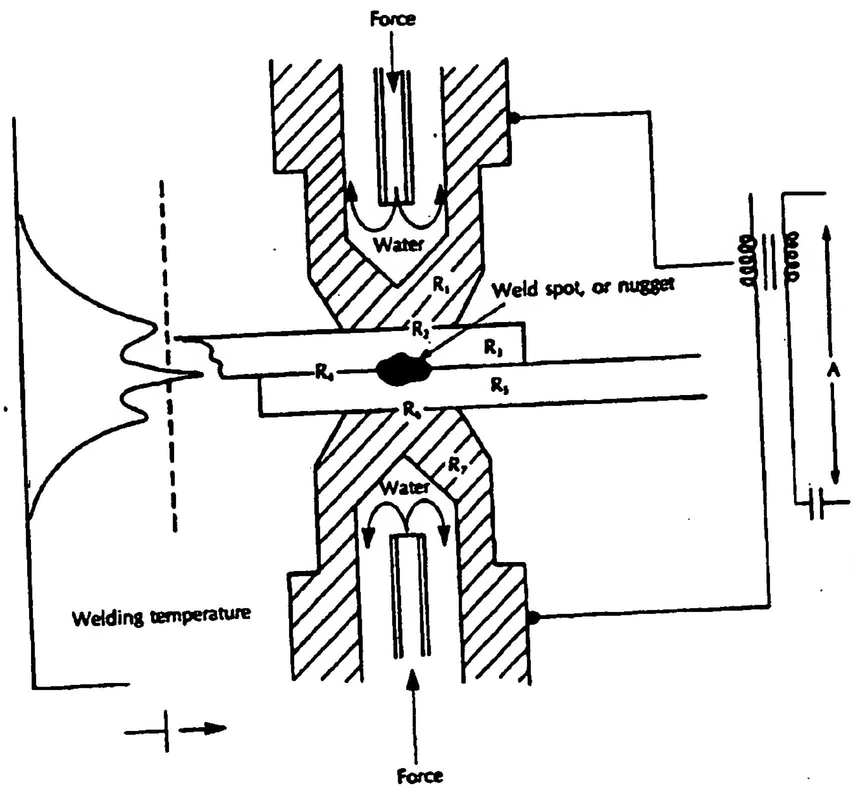


Figure 3.20 Schematic of the resistance (spot) welding (RSW) process showing it to be a circuit consisting of a series of resistors (R_1 through R_7), with heating intended to be greatest at the point(s) of contact of faying surface(s) between workpieces to create a weld nugget. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

electrodes, but not necessarily if there is another more favorable path, called a shunt, for the current. Spot welding usually requires access to both sides of the work, but can be accomplished from one side using a series-welding technique where current passes from one electrode on the face of the work, through the work to produce a weld at the interface of the workpieces, through the workpiece farthest from the electrode, back through the workpieces to produce a second weld, and into a second electrode contacting the front face of the work. Figure 3.22 schematically shows normal resistance spot and series resistance spot welds being made.

The purpose of the forging pressure cycle within the overall weld schedule of current and pressure versus time is multifold. First, pressure holds workpie-

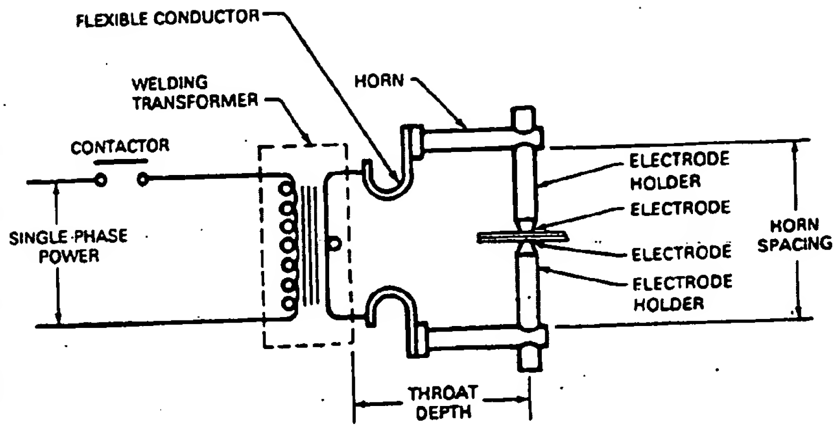
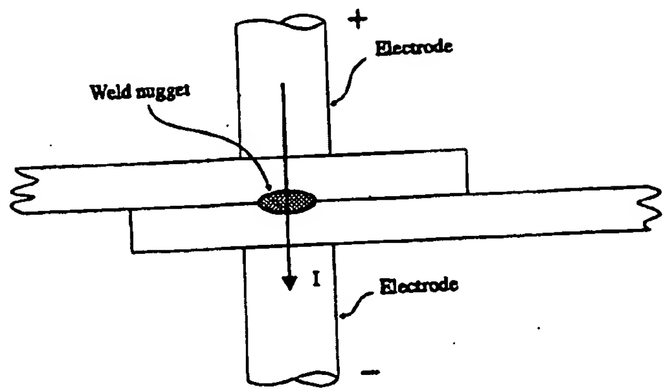


Figure 3.21 Schematic of a typical single-phase spot welding circuit. (From *Welding Handbook, Volume Two: Welding Processes*, 8th ed., R. L. O'Brien (Editor), published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

ces together to contain the molten nugget as it forms and expands as solid transforms to liquid. It is important to hold this liquid in the nugget under pressure, or it is expelled from the nugget at the faying surfaces. Expelled liquid (called expulsion or spitting) leaves insufficient liquid in the nugget to form a continuous solid weld. Large voids can result, seriously weakening the weld. Second, pressure is used to help control the contact resistance and, thus, rate of melting at the interface. Higher pressure lowers contact resistance by pressing more high points into intimate contact. Third, for some welding applications, pressure is needed to literally forge the work surfaces together in the vicinity of the weld. Use of pressure in this way is restricted to situations where surface indentations are tolerable. Incidentally, the ideal nugget in a two-ply joint from pieces with equal thickness is 0.6–0.7 of the combined thickness of the joint.

Resistance seam welding (RSEW) consists of a series of overlapping spots to produce an apparently continuous seam or resistance heating along the edges of two pieces being forced into contact along a seam in what is known as *mash welding*. Use of high-frequency AC or induction allows the edges of parts to be welded as they are brought together, perhaps by a continuous forming process. Figure 3.23 schematically shows a seam produced from overlapping spots made at the point of contact created by two opposing wheels (Figure 3.23a), with timed current pulses or groups of pulses producing each spot, as well as a seam along abutting edges of two workpieces as they are brought together (Figure 3.23b).

In projection welding (PW), projections or dimples in overlapping joint elements are employed to concentrate the current during welding, focusing the



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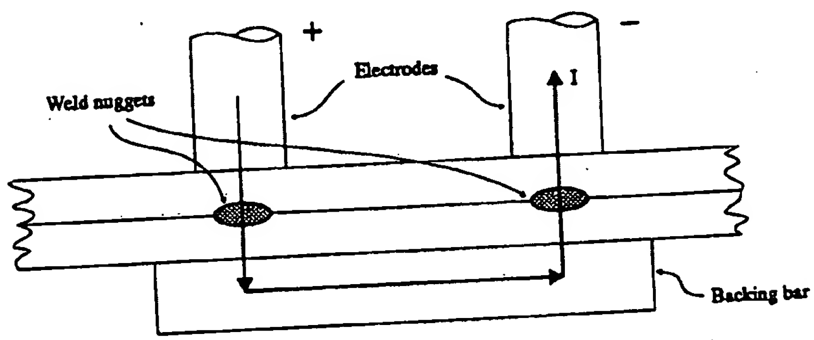

(b)

Figure 3.22 Schematic of (a) normal resistance spot welding (RSW) and (b) series spot welding.

weld energy and helping to locate the weld more precisely. Figure 3.24 shows projection welding schematically.

Figure 3.25 shows simple schematics comparing the three major resistance welding processes: spot, seam, and projection.

3.4.2. Flash, Upset, and Percussion Welding

Flash welding (FW) is classified as a resistance welding process, but it is unique. Heating at the faying surface is by combined resistance and arcing. Two parts

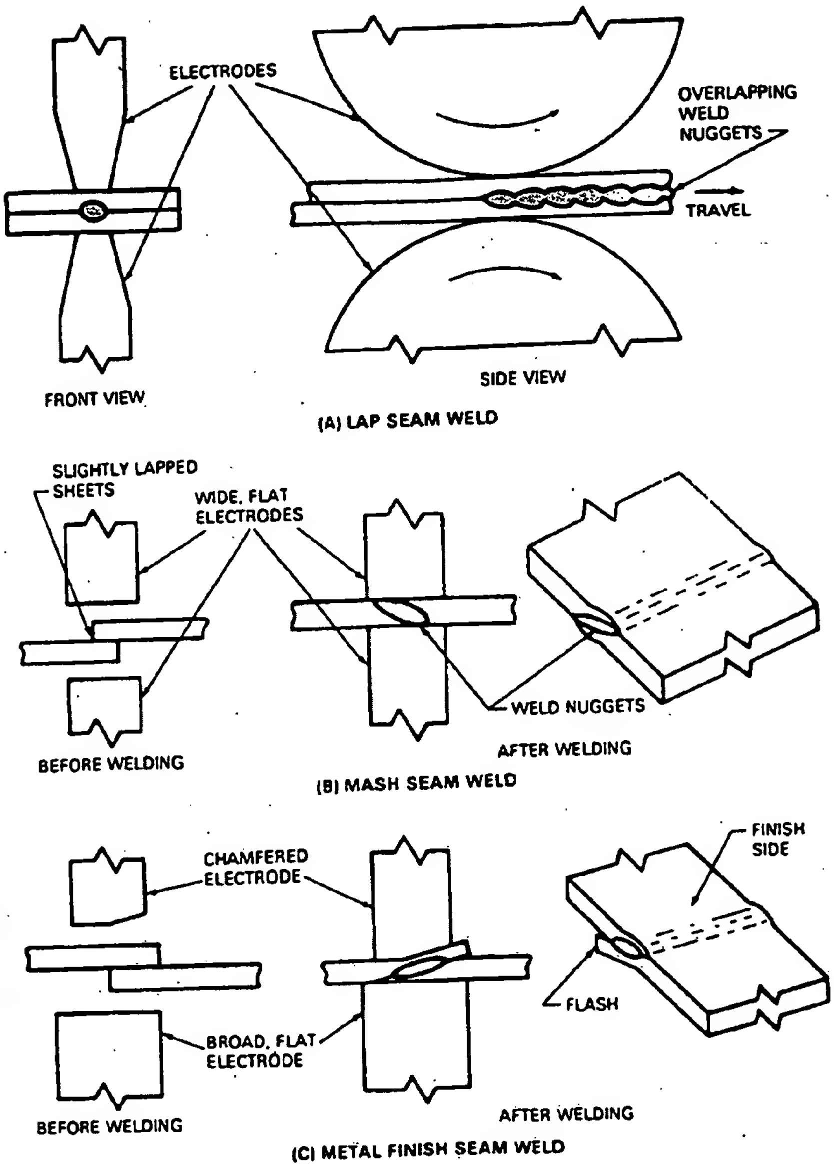

Figure 3.23 Schematic of (a) normal resistance-seam welding (RSEW) using overlapping spot welds, and (b) continuous seam welding as edges of two workpieces are forced together under the influence of a high-frequency or induced current (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

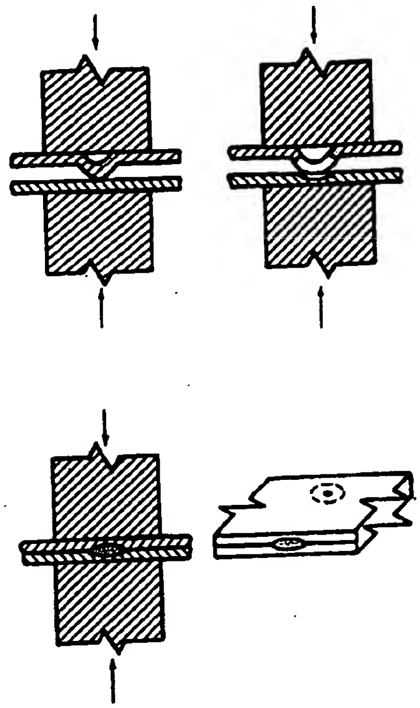

Figure 3.24 Schematic of projection welding (PW). (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

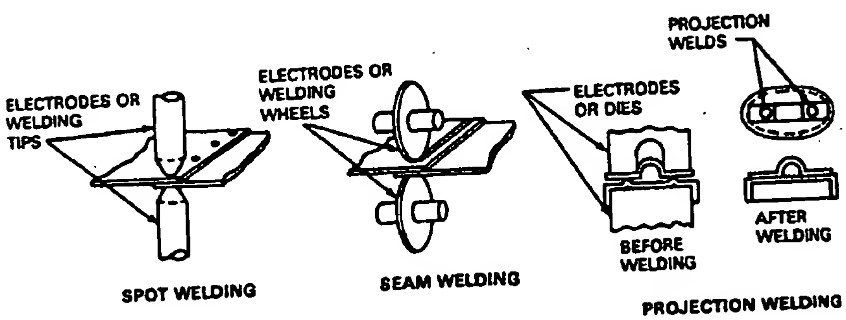

Figure 3.25 Simple schematics depicting the basic processes of spot, seam, and projection resistance welding. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

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to be welded are each made an electrode of opposite polarity by hooking them up into an electric circuit. As an initial gap between the two is reduced, high points on the faying surface of each begin to cause arcing, heat, soften and melt, and explode. Shortly after this point, the next highest points come into proximity and arc, heat, melt, and explode—and so on. This continues until the overall faying surfaces of parts to be joined are heated to a temperature sufficient to allow welding when a force is applied to consummate a weld. Molten metal is expelled, the hot metal is plastically upset, a weld is produced, and a "flash" of frozen expelled metal is formed.

Closely related to flash welding is *upset welding* (UW). The major differences are that the two parts to be welded are in contact from the outset of the process and the amount of gross plastic deformation or upsetting that is employed to produce the weld after suitable resistance heating of the entire joint area is much greater. Figure 3.26 shows flash welding schematically, along with a schematic of a typical flash weld, while Figure 3.27 shows upset welding and an upset weld schematically.

Percussion welding (also known as capacitor-discharge welding) produces welds through resistance heating by the rapid release of electrical energy from a storage device (e.g., capacitor). Figure 3.28 shows percussion welding schematically.

In all resistance welding processes, the rate of heating is extremely rapid, the time for which the weld is molten is extremely short, and the rate of cooling is usually rapid. This allows these processes to be used where heat input must be limited. On the other hand, resistance welding processes are capable of welding even the most refractory metals and alloys, due to the intense heating that can be made to occur (limited only by the current that can be applied, and the time for which it can be applied). High speed also allows the processes to be operated without shielding because of the combined effects of short time at temperature, limited access for air, and favorable effects of forging pressure to breakdown any oxide.

In RSW, RSEW, PW, and PEW, the presence of liquid is essential for the creation of a weld; thus, these are fusion welding processes, albeit ones that require substantial pressure. In FW and UW, on the other hand, liquid only serves to flux the faying surfaces, while forging (deformation) produces the weld, expelling virtually all of the liquid. In this sense, these two processes could be considered nonfusion pressure welding processes.

3.5. HIGH-INTENSITY RADIANT ENERGY OR HIGH-DENSITY BEAM WELDING PROCESSES

There is a group of processes that employs a source of high-intensity electromagnetic radiation to cause fusion and produce welds. The better known of these are the high-energy-density beam processes, including electron-beam and laser-beam welding. Less well known are those processes that employ a focused

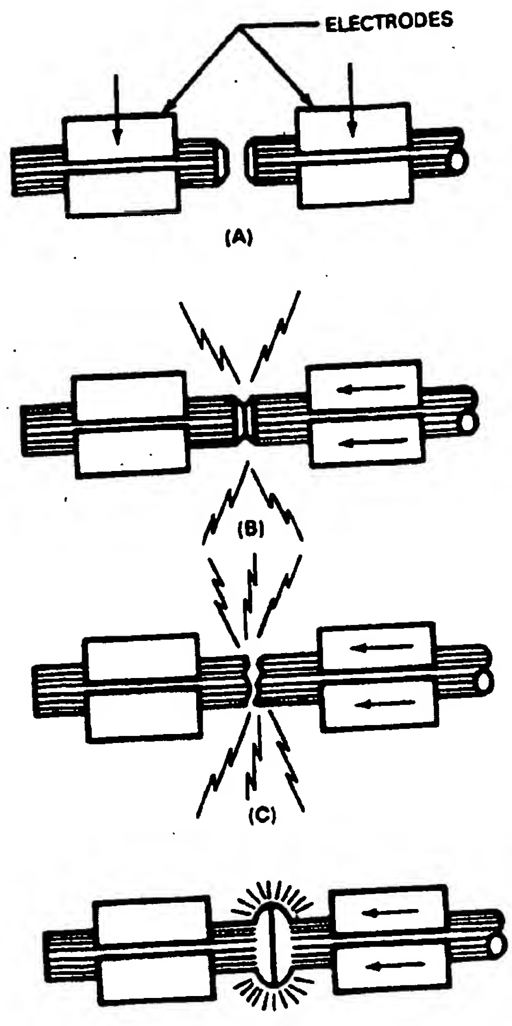

Figure 3.26 Schematic of (A through C) flash welding (FW) and a typical flash weld (D). (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

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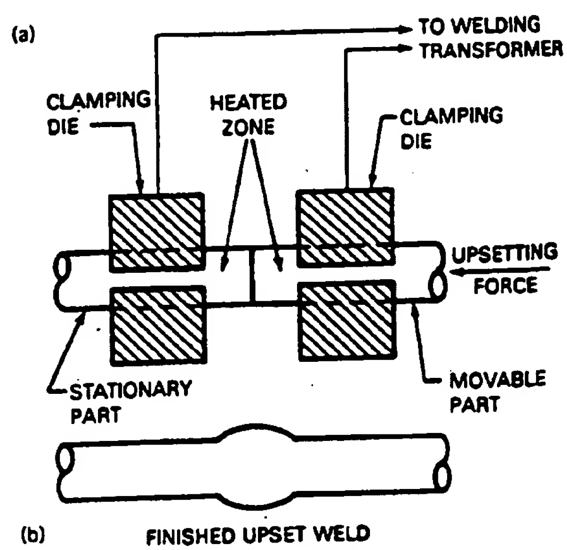

Figure 3.27 Schematic of (a) upset welding (UW) and (b) a typical upset weld. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.).

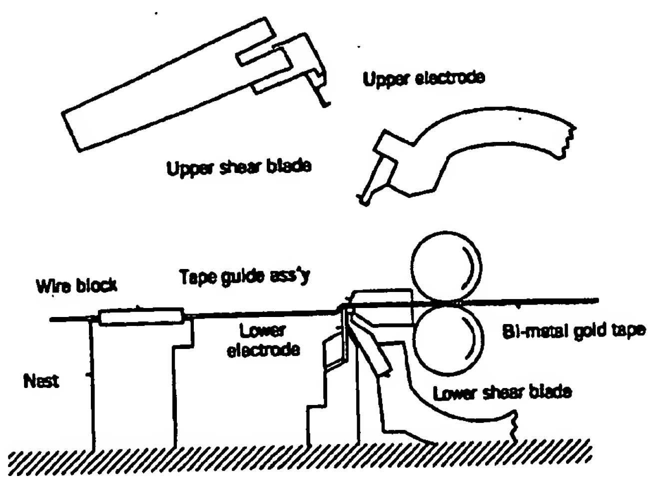

Figure 3.28 Schematic of percussion welding (PEW). (After "Principles and Practices in Contact Welding," by K. N. Petry, J. J. Buckenberger, J. E. Voytko, and D. R. Lipphart, *Welding Journal*, 49(2), 1970, published by and used with permission of the American Welding Society, Miami, FL.)

beam of electromagnetic energy to either heat a workpiece by concentration of the irradiating energy at the point at which it is absorbed or to excite the atoms comprising the workpiece to cause heating sufficient to lead to melting and weld production. These latter processes include focused IR and imaged arc welding and microwave welding, respectively.

3.5.1. High-Energy-Density (Laser and Electron) Beam Welding Processes

Often, the density of the energy available from a heat source for welding or for cutting is more important than the total source energy (as explained in Chapter 5). The two major types of high-energy-density welding processes are (1) *electron-beam welding* (EBW) and (2) *laser-beam welding* (LBW), although a third, yet to be developed possibility is ion-beam welding. Both processes use a very high-intensity beam of electromagnetic energy as the heating source for welding; the first in the form of electrons, the second in the form of photons. The energy density in both of these processes is approximately 10^{10} to 10^{13} W/m^2 versus 5×10^6 to 5×10^8 W/m^2 for typical arc welding processes. Conversion of the kinetic energy of the electrons (in EBW) or photons (in LBW) into heat occurs as these particles strike the workpiece, leading to melting and vaporization. Both processes usually operate in this keyhole mode, so penetration can be high, producing deep, narrow, parallel-sided (high aspect) fusion zones with narrow heat-affected zones and minimal angular distortion due to nonuniform weld metal shrinkage or thermal expansion and contraction.

The *electron-beam welding* (EBW) process is almost always performed autogenously,[14] so joint fit-up, usually as straight or square butts, must be excellent. Filler metal can be added as wire for shallow EB welds or to correct underfill in deep-penetration welds to improve cosmetics. It can also be added as preplaced shim stock. Laser-beam welding is usually done autogenously also, but can employ fillers unless penetration becomes excessive. Shielding for the EBW process is provided by the vacuum (typically, 10^{-3} to 10^{-5} atm) required to allow the beam of electrons to flow to the workpiece unimpeded by collisions with molecules in air or another gaseous atmosphere. Shielding for the LBW process is accomplished with inert gases, either in dry boxes or from special shrouds over the vicinity of the weld puddle, although the process could also be performed in vacuum.

While the high-energy beam of electrons in electron-beam welding is readily absorbed and the kinetic energy is converted to heat by all materials, this is not so for an intense beam of photons in laser welding. Some materials reflect photons, or light, depending on the specularity of the particular material and the wavelength of the photons or laser light. As a result, since the efficiency of

[14] It is possible to provide filler by preplacing shim material in the point, or by laying lengths of wire or shims in an underfilled weld and rewelding with reduced energy, partial penetration to improve the cosmetics of the weld crown.

electron absorption is high, the transfer efficiency of electron-beam welding is also high, approaching 90% and greater. Since the efficiency of absorption of photons can vary, process transfer efficiency can also vary, from a low of around 10% or less for highly reflective materials (like aluminum) to upward of 90% for nonreflective and absorptive materials (like graphite). Thus, penetration capability with laser-beam welding varies greatly, depending on material, and the process can be made to operate in either a melt-in or keyhole mode as a result.

Schematics of these two processes are shown in Figure 3.29.

Electron beams are produced in what is called a gun by thermionically extracting them from a heated filament or cathode and accelerating them across a high potential achieved using one or more annular anodes along a high-vacuum column. The stream of accelerated electrons is focused into a beam of very high energy density using a series of electromagnetic coils or lenses. The electrons then pass from the column to a work chamber to the workpieces to produce a weld. A typical gun, column, and work chamber are shown schematically in Figure 3.30. More details on the physics of EB welding can be found in Section 8.5.

While virtually all electron-beam welding is performed in a vacuum to prevent disruption of the high-speed/high-energy electrons by collisions with molecules in air or another gaseous atmosphere, there are exceptions. In fact, it has long been a goal to free electron-beam welding from the confines of a vacuum to make it more practical and less expensive due to the high capital cost of vacuum chambers. There are several possibilities, each with its drawbacks and each in a fairly to completely embryonic state of development.

First, there have been attempts to weld with beams of high-energy electrons in atmosphere. This can and has been done, although the distance between the beam source or exit from the source (called an electron-beam gun) and the work must be quite short (of the order of a few centimeters) to minimize interaction between electrons and gas molecules before interaction between electrons and the workpiece. A schematic of such a nonvacuum system is shown in Figure 3.31.

Very recently, there has been discussion of the potential of electron beams operating in the relativistic range. This means, the electrons have been accelerated by tremendously high-potential fields of millions of volts to near the speed of light. In this regime, it has been reported that the beam of electrons tends to remain focused and has minimal interaction with gas molecules, allegedly as the result of some electromagnetic pinching effect resulting from ionized atoms and molecules in the air.

More practically, there have been successes in welding in what is called a "soft" (as opposed to "hard") vacuum. Soft vacuums are generally only a tenth or a hundredth of an atmosphere of pressure, and can be obtained with differential pumping systems and a series of pressure locks. Examples of such systems have been used in the automotive industry to produce hermetically tight seals in components like catalytic converters.

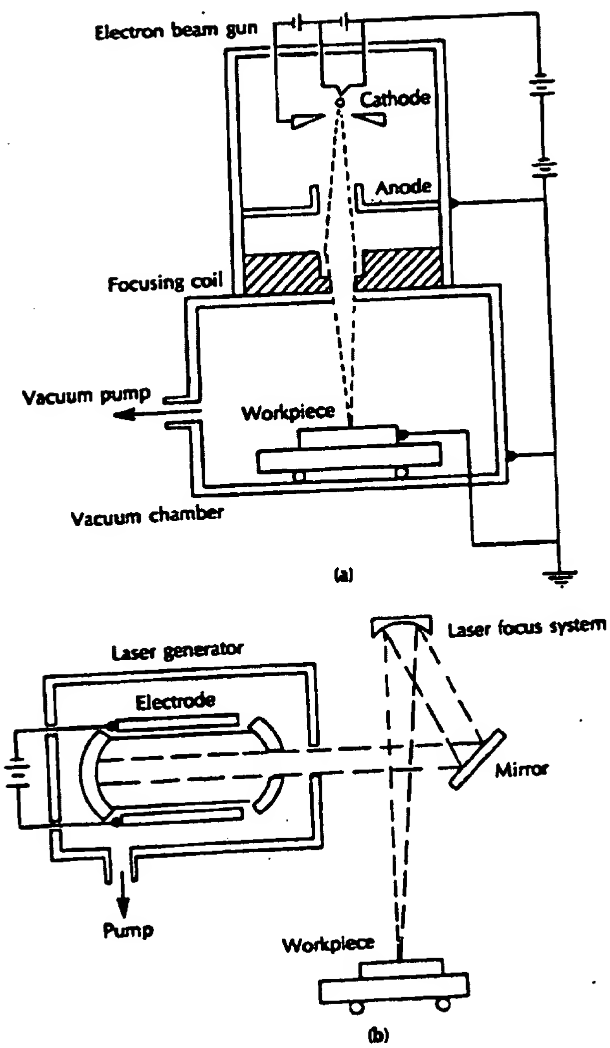

Figure 3.29 Schematic of (a) electron-beam welding (EBW) and (b) laser-beam welding (LBW) system. (From *Joining of Advanced Materials* by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.)

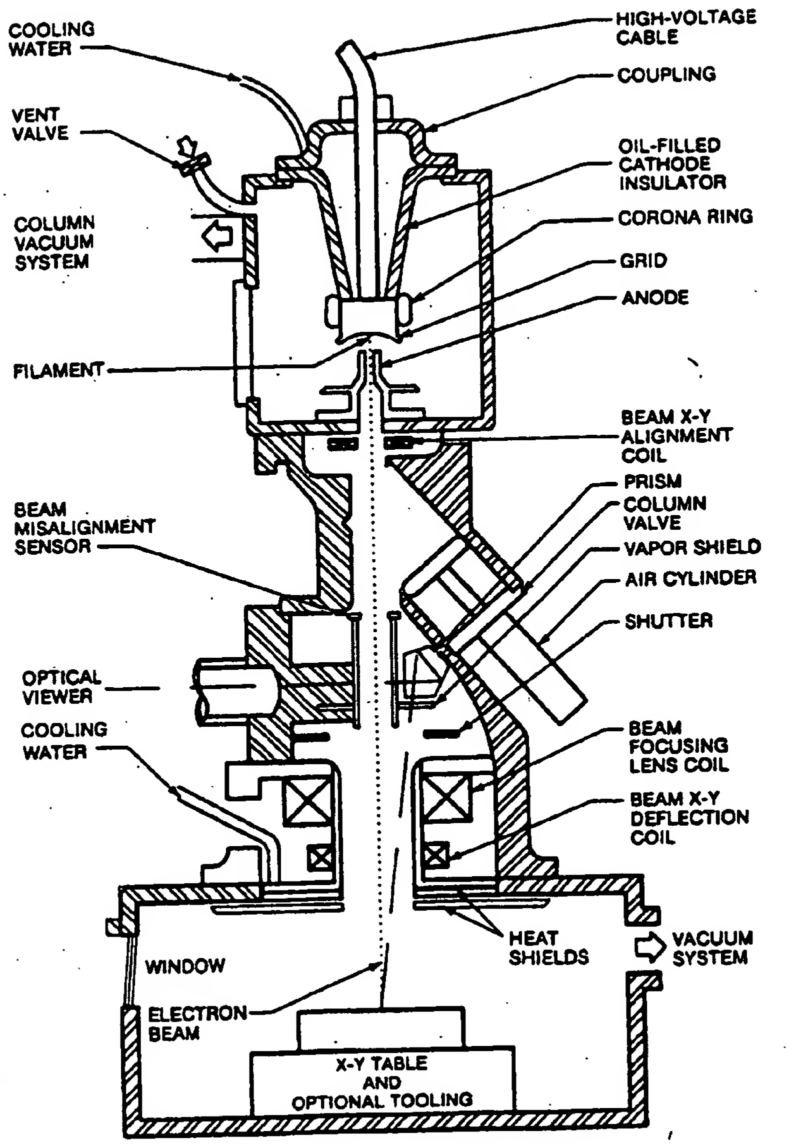

Figure 3.30 Schematic cross section of a hard-vacuum EBW gun, column, and work chamber. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th Edition, ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

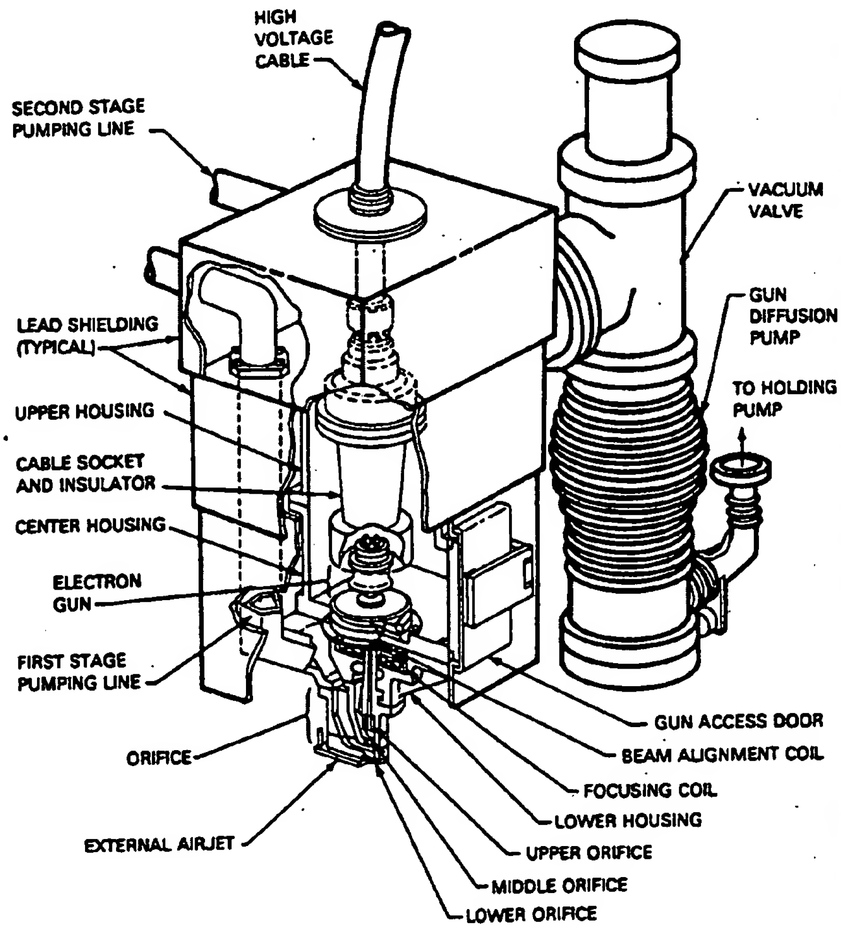

Figure 3.31 Schematic of a nonvacuum electron-beam gun column assembly. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

Finally, there has been success with what are called sliding-seal electron-beam or moving-chamber systems. In SSEB, rather than bringing the work to the vacuum environment to allow electron-beam welding to be performed, the vacuum is brought to the work. This is accomplished through the use of a small vacuum chamber, shaped to fit tight up against the workpiece, with the electron-beam weld executed through a system of holes and slots often moving the chamber. An example is shown in Figure 3.32.

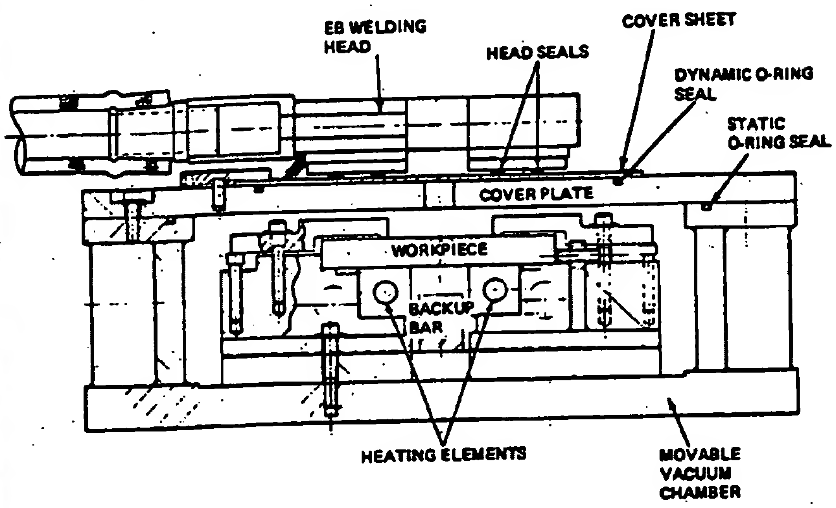

Figure 3.32 Schematic of a sliding-seal electron-beam (SSEB) welding system. (From "Sliding-Seal Electron-Beam Slot Welding of an Aircraft Wing Closure Beam," by R. W. Messler, Jr., *Welding Journal*, 60(9), published in 1981 by and used with permission of the American Welding Society, Miami, FL.)

The three basic modes of electron-beam welding, corresponding to three levels of vacuum referred to earlier, are shown schematically in Figure 3.33.

The sources for high-energy laser beams are of two types: (1) solid-state lasers and (2) gas lasers. The principal example of the former is Nd:YAG, while the principal example of the latter is CO^2. Schematics of a solid-state and a gas laser are shown in Figures 3.34 and 3.35. Without going into details here, there are three types of gas laser sources: (1) slow axial flow, (2) fast axial flow, and (3) transverse flow. Each type has its relative advantages and disadvantages, and the interested reader is referred to some excellent sources given at the end of this chapter. Schematic illustrations of each type are shown in Figure 3.35. Details of the physics of LB welding (as well as EB welding) can be found in Section 8.6 (and 8.5).

Comparative advantages and disadvantages of the two processes are given in Table 3.3. For both processes, three of the most significant advantages are (1) virtually unlimited melting power (due to the energy and energy density available in the beams); (2) precise placement of energy (due both to the fineness of the beam and the accuracy of beam focusing and delivery systems using optics or electrooptics); and (3) precise control of energy dosage (through source electronics). Both processes have also demonstrated the potential for use in outer space, to help fabricate structures there. The high depth-to-width ratio of LBW operating in the keyhole mode and, especially, EBW welds versus

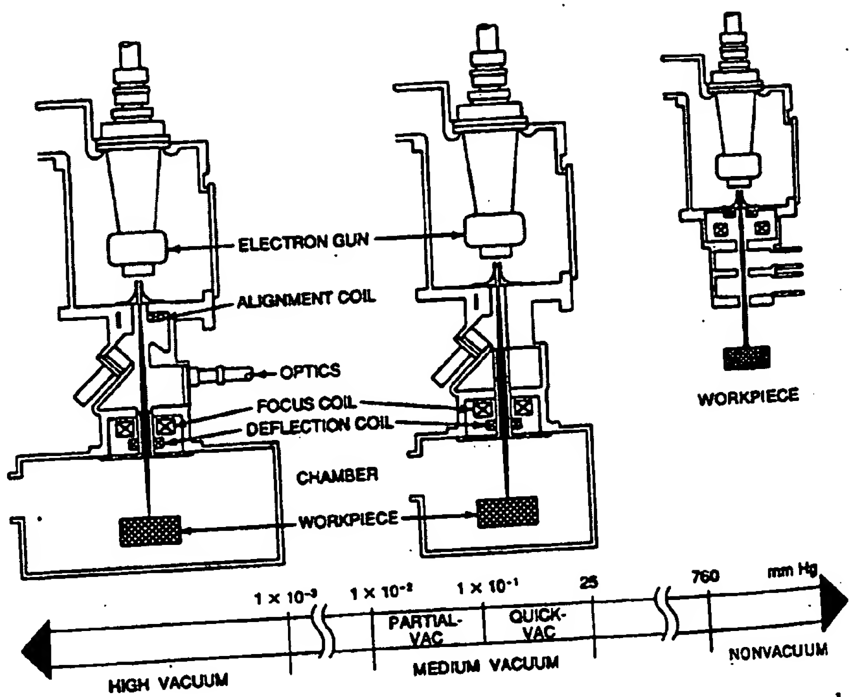

Figure 3.33 Schematic of the three basic modes of electron-beam welding, corresponding to three levels of vacuum. (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

welds made by conventional arc welding processes is shown schematically in Figure 3.36.

3.5.2. Focused IR and Imaged Arc Welding

Rather than using the radiation of an extremely intense beam of electromagnetic energy in the form of electrons (in EBW) or monochromatic and coherent photons (in LBW), it is possible, although much less common, to simply use focused light. The two possibilities are *focused IR* and *imaged arc welding* processes.

Infrared radiation from the sun or an artificial light source can be used to make welds provided the radiation is focused into an intense, high-density spot directed onto the work. When the sun is used, the process (although rare) is called solar welding. Artificial IR sources are often high-intensity, quartz heat lamps that produce light with a wavelength of about 1 μm. Figure 3.37 shows a focused IR system schematically.

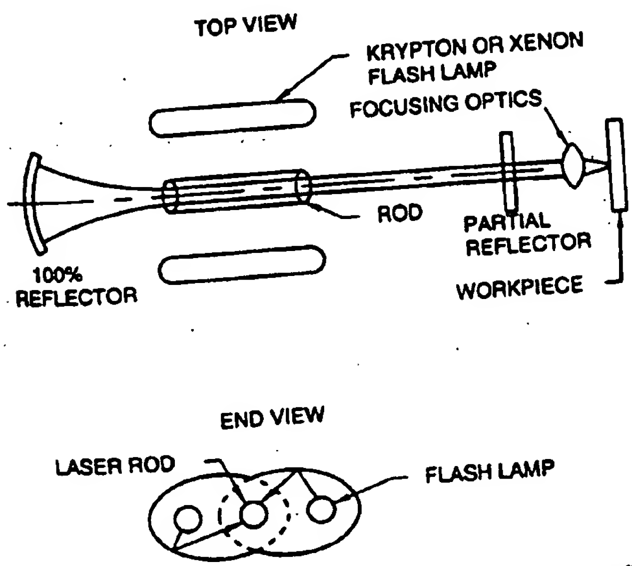

Figure 3.34 Schematic of a solid-state laser source (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

Because the heating power of focused IR sources is limited, the process (especially using artificial sources) is most often used to weld thermoplastic polymers, but could be used to weld low-melting point metals (e.g., Pb, Sn, and Zn or their alloys, pewter, babbitt metal, etc.). For some polymers, a through-transmission variation has been developed. Here, the IR radiation is passed through a transparent polymer to an absorbing interface. At this interface, the IR is absorbed, the interface heats and melts, and a weld is made. Xenon lamp sources have also been used for flash soldering by reflow. The principal advantage of focused IR welding is relative low cost, especially if the source is the sun. However, there are, without question, practical problems in capturing, focusing, directing, and moving the energy.

In a process known as *imaged arc* or *arc image welding*, little or no information seems to be available, and most of what is known by the author (and many others) is anecdotal. In principle, what is done is to focus a high-intensity electric arc or plasma arc using suitable optics largely relying on reflection using parabolic mirrors. The imaged arc is then directed onto the workpieces, intense heating and melting takes place, and a weld is made. An obvious and possibly useful advantage is freedom from the electromotive Lorentz forces associated with conventional arc welding, which can lead to unwanted induced currents and arc deflection (see Section 8.1) or weld pool convection (see Section 9.1.3).

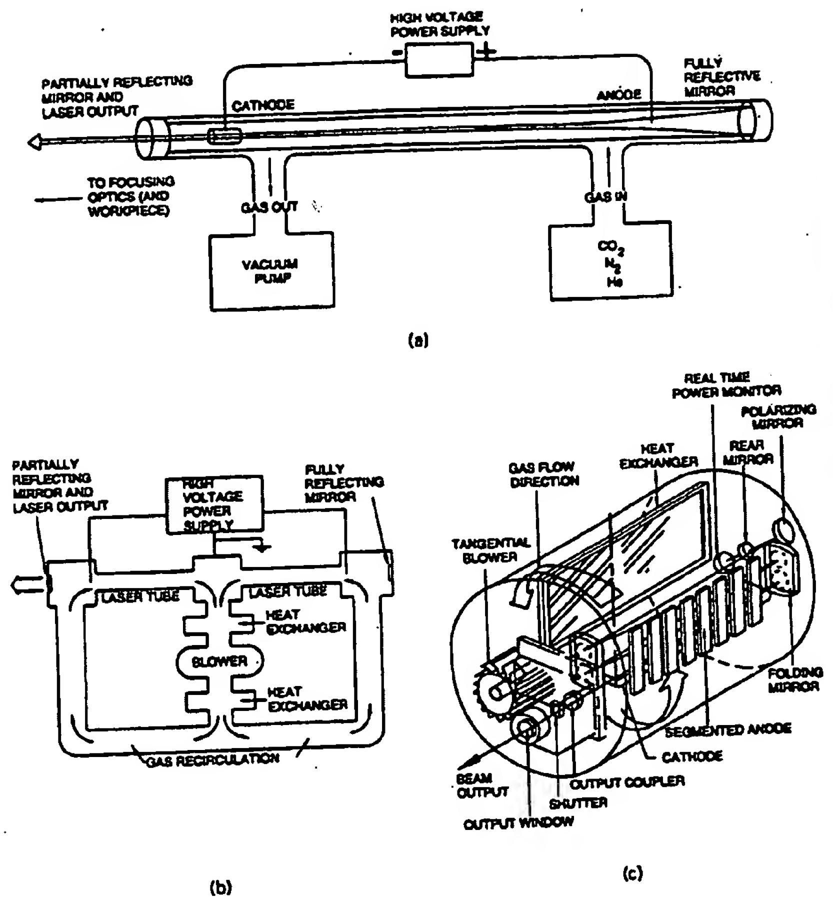

Figure 3.35 Schematic of (a) slow axial flow, (b) high axial flow, and (c) transverse flow lasers (From *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., edited by R. L. O'Brien, published in 1991 by and used with permission of the American Welding Society, Miami, FL.)

3.5.3. Microwave Welding

The use of induction heating, as employed in some variations of resistance welding, is reserved for conductive materials (chiefly metals and alloys) in which eddy currents can be produced to generate thermal energy by Joule I^2R heating. In the case of nonconductive materials, in which direct Joule heating by induction methods is not possible, a related process called *high-frequency dielectric heating* can be used. The process is called microwave heating and can

TABLE 3.3 Comparative Advantages and Disadvantages of Electron-Beam and Laser-Beam Welding Processes

EBW	LBW
1. Deep penetration in all materials	1. Deep penetration in many materials, but *not* in metals that reflect laser light of specific wavelengths because they are specular or because their vapors are reflective
2. Very narrow welds	2. Can be narrow (in keyhole mode)
3. High energy density/low linear input heat	3. Same
4. Best in vacuum, to permit electrons to move unimpeded	4. Can operate in air, inert gas, or vacuum
5. Usually requires tight-fitting joints	5. Same
6. Difficult to add filler for deep welds, except as preplaced shim	6. Same
7. Equipment is expensive	7. Same
8. Very efficient electrically (99%)	8. Very inefficient electrically (~12%)
9. Generates x-ray radiation	9. No x-rays generated

Source: Joining of Advanced Materials by R. W. Messler, Jr., published in 1993 by and used with permission from Butterworth-Heinemann, Woburn, MA.

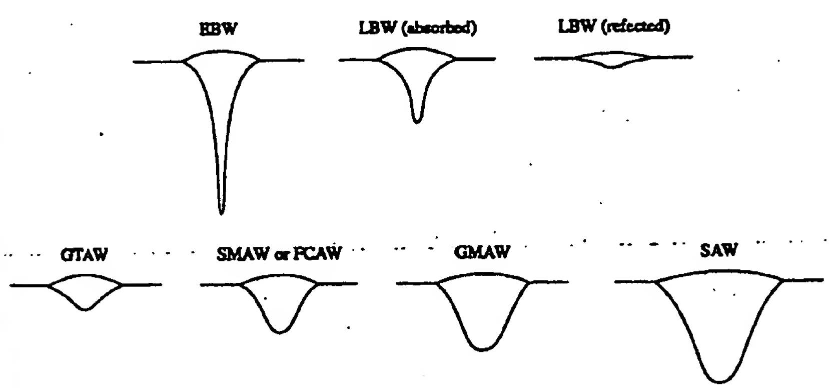

Figure 3.36 Schematic comparison of typical EB, LB, and conventional arc (e.g., GTA, GMA, SMA, FCA, or SA) welds.

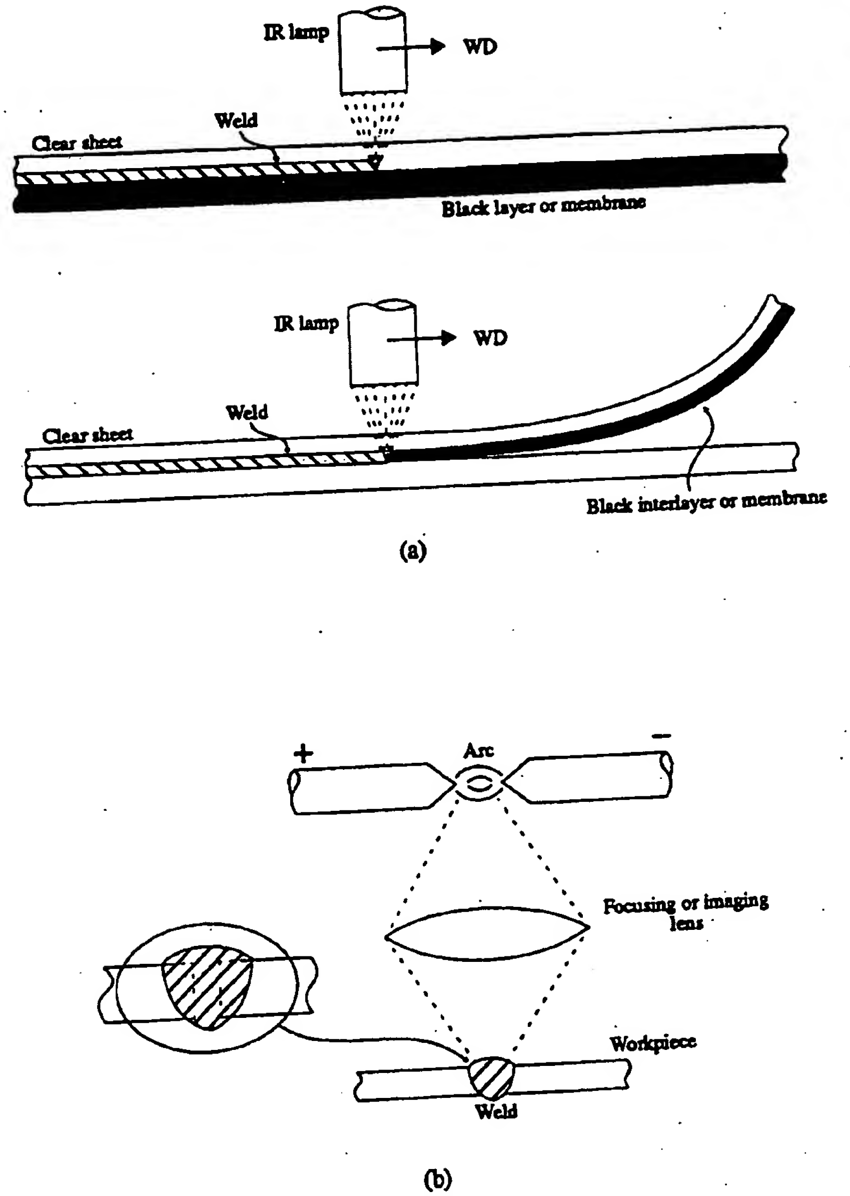

Figure 3.37 Schematic of (a) the focused IR and (b) imaging-arc welding processes.

be the basis for welding, as well as brazing and soldering. Microwave heating dates back to the 1930s when it was used to vulcanize rubber (Puschner, 1966). More recently, it has been used to dry wood and textile products as well as grain and sugar.

The use of microwave electromagnetic radiation (in the frequency range of approximately 0.05–50 GHz, with some limitations, since this frequency range is shared in use for radio transmission/reception) as a means of heating materials is well known from that time-saving appliance, the microwave oven. Similar in principle, *microwave welding* uses the energy of microwaves to cause ions or polar molecules to oscillate rapidly, producing heat from inside the material. Unlike the kitchen appliance, which operates with a microwave source of several hundred watts at a frequency of 2.54 GHz, sources used for welding are capable of delivering thousands or tens of thousands of watts at frequencies from 5 to 50 GHz or more.

For there to be an interaction between the electromagnetic microwave energy and the material, the material must be composed of or at least contain either ions or polar molecules, that is, it must be a nonconducting dielectric, rather than a conductor. Thus, ceramics and polymers are normally heated and welded using microwave sources. Metals can be heated indirectly by being placed in a ceramic vessel, which is heated by the microwaves and, in turn, heats the metal by conduction.

Two types of microwave generators are employed: (1) magnetron sources and (2) klystron tube sources. Both sources employ a waveguide to direct the field energy. The magnetron source is capable of frequencies up to 1 GHz and power levels up to hundreds of kilowatts, with power capability decreasing with increasing frequency. Magnetrons are the preferred source for industrial applications of microwave energy. Klystrons are used to generate microwaves at higher frequencies. Waveguides are used as "horns" to direct the microwave energy from the source to the target workpiece(s). While simple in geometry (usually just rectangular tubes), the dimensions are precisely controlled to prevent unwanted attenuation of the microwaves from the source on their way to the target.

Research has shown that several different ceramics can be welded by heating to above or near the point of melting. A key to the microwave welding process is achieving coupling between the microwave energy and the material. What is meant here is that different materials absorb microwave (MW) energy to a greater or lesser extent, depending on (1) the materials character (whether it is composed of ions or polar molecules, and what ones); (2) the frequency of the MW energy (due to loss factor effects); and (3) the temperature of the material being irradiated (with absorption increasing with increasing temperature). To produce a weld between two pieces of ceramic of similar or different type and/or composition, the interface is often packed with a mixture of the ceramics in powdered form along with powdered glass or frit. This mixture tends to preferentially absorb the MW energy, and thus preferentially heat, and soften or melt.

Microwave welding is, for the most part, in an embryonic state, except as it is being used for welding plastics. The process has tremendous potential, however, for hard-to-weld ceramics.

Figure 3.38 shows schematically how microwave welding occurs.

3.6. SUMMARY

A large number of very diverse processes are dependent on melting a portion of the substrate(s) followed by solidification to cause metallic continuity to produce a weld. These are collectively called fusion welding processes. Major groups include (1) processes employing a chemical energy source, including (a) gas welding employing a combustible fuel as the source of heat, or (b) an exothermic solid-phase (aluminothermic) reaction as the source of heat; (2) processes employing an electric arc as the energy source, including arcs between (a) a nonconsumable electrode as a source of heat, or (b) a consumable electrode, as a source of both heat and filler metal; (3) processes that develop heat by internal resistance or Joule heating of the workpiece, whether

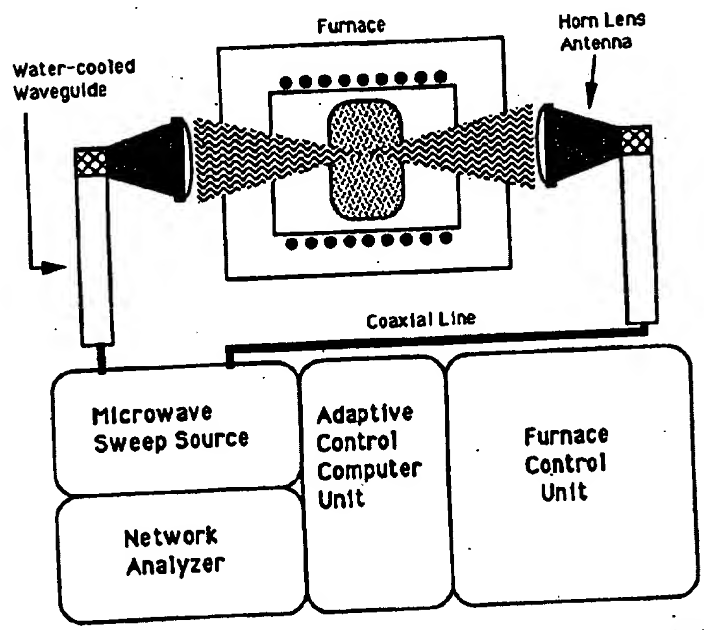

Figure 3.38 Schematic of a microwave welding system. (From *In Situ Monitoring of Porosity in Alumina During Sintering Using Ultrasonic and Microwave Energy*, Thesis, P. Komarenko, May 1992, Rensselaer Polytechnic Institute, Troy, NY, with permission.)

as the result of direct current flow in a circuit or currents induced in a part; and (4) processes that develop heat from a high-intensity radiant energy or beam source through the conversion of the kinetic energy of fast-moving particles in that irradiating beam.

The diversity of types is the reason fusion welding processes predominate in the fabrication of weldments as well as the overlaying, cladding, or hardfacing of parts, in both number of applications and tonnage of product produced.

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